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Future of Industry 4.0 and Emerging Technologies of Industry 5.0: Study

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Abstract: ***The Industrial Revolution refers to the shift from traditional industrial practices to new techniques driven by contemporary technologies. The first three revolutions were powered by mechanization, electrification, and automation, transforming economies from agrarian to manufacturing-based. These changes improved factory workers' living standards, healthcare, and overall quality of life, while boosting production, competitiveness, and global business. Currently, we are experiencing the Fourth Industrial Revolution (Industry 4.0), with the world preparing for the next phase: the Fifth Industrial Revolution (Industry 5.0). The first part of the paper explores the technologies of Industry 4.0 and their role as a foundation for Industry 5.0, as well as the socio-economic challenges and the need for advancements in Industry 5.0. The second part discusses potential technologies for Industry 5.0, their applications, and how they can address the challenges of Industry 4.0.***

Keywords: Industry 4.0, Industry 5.0,

1. Introduction

In the early 1800s, the world began the Industrial Revolution, marking the shift from an agrarian society to industrialization and urbanization. [1] Coal, water, and steam powered large engines used in textiles and manufacturing. As a result, many people left rural farming villages to work in factories in nearby cities. This transformation started in Britain before spreading to Europe and America. [2] The second Industrial Revolution, occurring in the late 1800s and early 1900s, was driven by science-based innovations such as mechanized agriculture, textile industries, railroads, internal combustion engines, electric power, and iron and steel production. Vaclav Smil, a Czech Canadian scientist, described the period from 1867 to 1914 as the "age of synergy," which laid the groundwork for 20th-century advancements.[3]

However, both industrial revolutions were marked by poor, dangerous working conditions, which led to the formation of labour unions and factory regulations to protect workers. The third Industrial Revolution began in the 1950s with the development of transistors and microprocessors, enabling automated production supported by electronic devices. Digital sensors and computers were integrated into manufacturing processes. While working conditions improved, labor exploitation continued, cities became overcrowded, and pollution and environmental damage increased globally. The ongoing Fourth Industrial Revolution, or Industry 4.0, builds on the third revolution, using technologies like sensors, transistors, and microelectronics to generate data. The term "Industry 4.0" was coined by German Professor Wolfgang Wahlster in 2011 at the Hannover Fair. It refers to the digital transformation of manufacturing, focusing on automation, interconnectivity, and real-time process optimization through technologies such as the Internet of Things (IoT), Machine Learning (ML), Artificial Intelligence (AI), Cyber-Physical Systems (CPS), Cloud computing, Additive Manufacturing (AM), Digital twins, and Cybersecurity. [4,5] This revolution integrates advanced digital technologies with industrial machines and processes to achieve greater efficiency, productivity, and automation, creating a smart, connected, and data-driven manufacturing ecosystem.

The core model of Industry 4.0 combines digital technologies with physical systems. Key digital technologies like AI, Machine Learning (ML), Big Data, Cloud Computing, and Cybersecurity are paired with physical technologies such as Automation, Robotics, Internet of Things (IoT), Cyber-Physical Systems (CPS), and Additive Manufacturing (AM). Together, these technologies enable flexible, on-demand, and agile manufacturing, which is crucial for smart factories.[6]

While these advancements offer industries competitive advantages and increased efficiency, concerns about job losses for low-skilled workers due to high automation are widespread, potentially leading to economic inequality. As the world adapts to Industry 4.0, some experts and industrial leaders are already looking ahead to Industry 5.0. Unlike Industry 4.0, which focuses on machine interconnectivity and optimization, Industry 5.0 aims to reintroduce human collaboration in manufacturing, focusing on sustainability and the human touch in production. Elon Musk, CEO of Tesla, acknowledged the downside of excessive automation, admitting that it slowed production and that human involvement was crucial. This aligns with predictions that the future will feature closer collaboration between humans, robots, and digital technologies.[7] [8]

2. Need for the Study

Despite the ongoing adaptation of Industry 4.0 in various sectors and growing discussions on Industry 5.0, this paper aims to provide a brief background on the enabling technologies of Industry 4.0 and their application in various functions of manufacturing industries, the prospective Industry 5.0 technologies and their potential applications and attempts to answer the following five research questions (RQ),

RQ1. What are the enabling technologies of Industry 4.0 and their application in manufacturing industries?

RQ2. What are the socio-economic challenges of Indus- try 4.0 technologies? Why must the industries overlook these technologies and upgrade to the prospective Industry 5.0 technologies?
RQ3. What are the prospective technologies of Industry 5.0 and their application in manufacturing industries?
RQ4. What is "sustainability trilemma" and how does Industry 5.0 technologies help to overcome it?
RQ5. Why "Industry 5.0" must be called "Industry 4.0S"?

3. Enabling technologies of industry 4.0

3.1 Artificial intelligence (AI)

Artificial Intelligence (AI) refers to algorithm-based intelligence that enables machines to solve problems, make decisions, and perform tasks similar to humans. It is a key driving force of Industry 4.0, combining various digital and software technologies. AI's origins trace back to the 1940s, with significant advancements in the 1980s. Subsequent developments in algorithms like statistical learning, Greedy learning, Recurrent Neural Networks (RNN), and Deep Belief Networks have continuously expanded AI's capabilities.[9]

In Industry 4.0, AI has shown strong potential in areas such as predictive maintenance, analytics, inventory management, machine vision, robotics, and supply chain management. For instance, AI-driven algorithms like k-NN, Naive Bayes, Artificial Neural Networks (ANN), and Deep Learning have been used for fault diagnostics in machinery, reducing downtime, maintenance costs, and safety risks. As each algorithm has its own strengths and weaknesses, researchers suggest developing hybrid intelligent systems to tackle future challenges.

Several applications include the use of RNN for predictive maintenance in machines, forecasting tool wear, and diagnosing faults in gearboxes and bearings. Deep Belief Networks have been employed to establish relationships between operational parameters in manufacturing, such as polishing operations and material removal. These techniques have also been used to predict the lifespan of hybrid ceramic bearings. Given the complex and unpredictable nature of manufacturing processes, AI is essential for improving efficiency and reliability.[10]

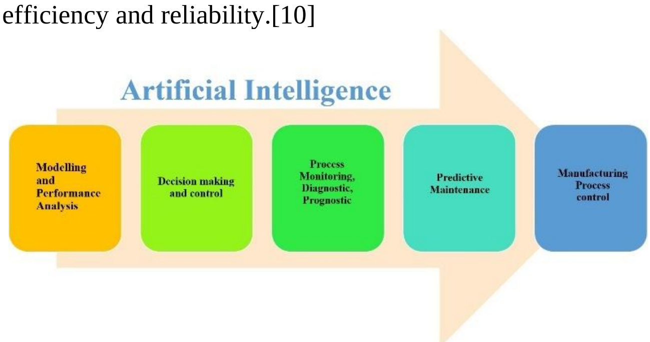

Figure 1: Opportunities of AI in a manufacturing system

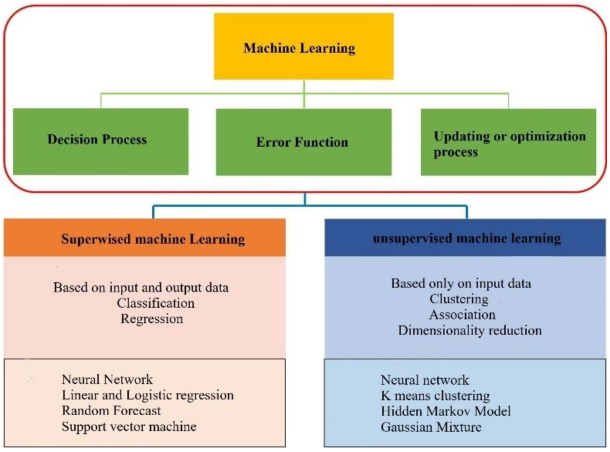

Figure 2: Supervised and unsupervised machine learning algorithm

uncertainties many researchers have tried different AI-based techniques to enable the optimal material flow. The potential opportunities of artificial intelligence in the manufacturing industry are shown in Fig. 1.

3.2 Machine learning (ML)

ML enables systems to exchange data and autonomously enhance processes using algorithms. This iterative learning and optimization lead to exceptional performance, transforming traditional factories into smart factories. In manufacturing, ML is applied in areas like machinery condition monitoring, health monitoring of structures, predictive maintenance, quality control, and supply chain management. By processing sensor data, ML algorithms can identify failure patterns and predict future issues, reducing the need for manual inspections. Combining ML with machine vision allows for automatic, real-time detection of defective parts without human involvement.

In business, ML is also used to predict consumer behaviour and manage supply chains, helping manufacturers avoid issues like overstock or stockouts, which can negatively impact profits. ML algorithms have been effective in demand forecasting and inventory management. Beyond manufacturing, ML is widely used in everyday applications like speech recognition (e.g., Alexa, Siri), customer service bots, computer vision (e.g., self-driving cars), recommendation engines (e.g., search engines and e-commerce), and automated stock trading.

3.3 Big data & analytics

Big Data refers to vast amounts of data that are generated at high speeds, often measured in petabytes or zettabytes. This data is analysed using advanced techniques to identify patterns and correlate them with specific behaviours, aiding decision-making. Initially defined by the 3Vs (Volume, Variety, and Velocity), Big Data's characteristics have been expanded by researchers to include additional "V"s, such as Variability, Veracity, and Value. With the rise of artificial intelligence, connected sensor systems, social media, and digital communication devices, massive data is generated continuously, requiring real-time processing for faster decision-making. The concept of Big Data dates back to the 1960s when the first database management systems and data centres were developed to store data. Over time, with the growth of high-speed internet, more physical objects became connected through the Internet of Things (IoT), resulting in even larger data volumes.

Storing and managing large volumes of data presents significant challenges. According to a report by Oracle, organizations are struggling to keep up as data generation doubles annually. The primary difficulty is not just storing the data, but in the process of data curation, which involves cleaning unwanted data, processing, analyzing, and securing it. This ensures granular access to extract valuable insights for informed decision-making. Additional challenges related to Big Data.

3.4 Cloud computing and cloud manufacturing

Cloud computing refers to the delivery of networking and computing services over the internet, offering services such as server, storage, database, networking, analytics, and intelligence. It is cost-effective and flexible, providing benefits like reliability, scalability, and centralized management of data and software. The infrastructure is managed by IT service providers, while businesses and individuals can access it on-demand through various internet services. The three main cloud service models are Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS), with deployment models including public, private, and hybrid clouds.[10]

In manufacturing, cloud computing is adopted in two ways: directly integrating digital technologies for “cloud computing in manufacturing” and through “cloud manufacturing.” Cloud manufacturing involves the integration and distribution of manufacturing resources like software, machines, and capabilities to manage the product lifecycle. [11]

This enables the concept of "design anywhere, manufacture anywhere," improving efficiency, cost-effectiveness, and flexibility. Technologies like IoT, RFID, sensors, GPS, cyber-physical systems, and cloud computing are key enablers of cloud manufacturing. Design engineers can access resources remotely, speeding up lead times, while manufacturing engineers can access resources anytime, even off-site, ensuring uninterrupted production. Cloud manufacturing also enhances supply chain efficiency and reduces costs by storing parts digitally and manufacturing them on demand.

3.5 Cyber security

As industries increasingly adopt Industry 4.0 and connect more isolated systems to the internet, the risk of security vulnerabilities such as data theft, malware, denial of service, and device hacking grows. Cybersecurity is essential for protecting these connected systems from malicious attacks. Manufacturing, in particular, faces heightened vulnerability due to less stringent regulatory compliance, complex security systems, disparate technologies, and a lack of in-house expertise.[12]

According to Honeywell's "Industrial USB Threat Report 2021," threats exploiting removable storage devices, like USB drives, have risen significantly, from 19% in 2019 to 37% in 2020. Additionally, 79% of these threats could completely disrupt operational technology. The report also notes a 30% increase in the use of USB drives, highlighting the security risks industries face. Another report from IBM reveals that the average cost of a data breach has risen from $3.86 million to $4.16 million globally, the highest in 17 years. [13]

Common cybersecurity threats targeting industries include ransomware, insider attacks, credential theft, remote access trojans, and business email compromise. IBM outlines eight major cybersecurity domains to protect against information theft.

Cyber-attack on Ukraine’s power grid infrastructure in 2015 through a malware-infected email was the first known attack on the power infrastructure which shows the vulnerability of physical industrial assets [83]. The various risks, security requirements, and the impact of threats to the businesses as outlined by Corallo et al. [84] are summarized in Table 4.

The studies show that although implementing digital technologies on a factory shopfloor has a huge potential, businesses must be cautious of the increasing cyber threats, and they must develop and invest in suitable data security programs to get the real benefits of Industry 4.0 transformation.

3.6 Automation and robotics

Automation and robotics are closely linked, both designed to improve industrial productivity by working independently and efficiently. By connecting robots to centralized computer systems, their tasks can be controlled without human intervention. Advanced machine vision techniques, using high-resolution cameras on robotic arms, allow robots to track objects in real-time and perform tasks like identifying and removing defective parts.[14]

While robots have been used in industries for decades, those in Industry 4.0 will feature advanced sensors, control algorithms, communication channels, and data processing capabilities. Key differences between earlier and current-generation robots include their ability to self-learn, flexibility, and agility, supported by complex neural networks.[15]

In Industry 4.0, automation and robotics are crucial for performing dangerous tasks, ensuring continuous production, improving reliability and productivity, data extraction, working in harsh environments, and handling monotonous tasks. Other applications include material handling, customer service, surveillance, and assembly line management. These tasks are enabled by various digital technologies.

Robotic Process Automation (RPA) is another technology transforming organizations, particularly in automating routine ERP-related tasks. RPA, also called a "digital worker," uses AI, text recognition, and language processing to automate tasks like signing into software, data editing, email replies, report generation, and invoicing. However, RPA's main limitation is that it works based on simple rules, making it less effective for for complex, data-intensive decision-making. Combining RPA with machine learning (ML) can help overcome this limitation.[16]

3.7 Internet of things (IoT) and industrial internet of things (IIoT)

The Internet of Things (IoT) refers to a network of physical objects integrated with sensors, software, and digital technologies that enable them to connect and communicate over the internet. The key distinction between IoT and Industrial IoT (IIoT) is the type of devices connected. IoT typically refers to devices used in consumer applications like smart home appliances and health trackers, while IIoT involves industrial devices that support operations like manufacturing, quality control, and supply chain management.[17] The fourth industrial revolution centers on creating communication channels through the internet to facilitate two-way data flow between humans and machines, as well as between machines. The small, cost-effective IoT sensors allow for the connection of more objects, making systems smarter, more efficient, and safer.

In manufacturing, sensors collect real-time data on various factors such as temperature, [18] pressure, and vibration, helping to optimize product performance, reduce costs, and support preventive maintenance. By identifying malfunctions early, IoT systems can prevent production line stoppages, saving time and improving efficiency.[19] Research has shown that IoT systems can be used in predictive maintenance, anomaly detection, and error prediction. For example, sensors combined with AI models have been used to monitor the health of engine systems and predict tool wear. IoT is also useful in hazardous environments like nuclear power plants and chemical factories, where it helps monitor and control operations. However, as more devices connect, protecting sensitive information becomes increasingly complex, requiring advanced safety algorithms.[20]

3.8 Cyber-physical systems (CPS)

A cyber-physical system (CPS) is an intelligent system that combines sensing, computation, control, and networking capabilities into physical objects, connecting them to the internet and each other. While IoT and CPS share similarities, the key difference is that IoT focuses on physical objects with sensors for data collection and transmission, while CPS includes components for computation and control, making it more efficient.

CPS has various applications, including in aviation, self-driving cars, energy, healthcare, smart cities, and smart manufacturing. In smart manufacturing, CPS can be used for monitoring production lines, asset management, predictive analysis, and supply chain management. A typical CPS framework consists of three layers: the physical layer, communication layer, and computation layer.[21] The physical layer includes sensors, GPS, RFID, cameras, and IoT modules that gather real-time data and send it to the communication layer. The communication layer is responsible for transferring this data via networks like LAN, WAN, Bluetooth, and Wi-Fi to the cyber computation layer. The computation layer processes the data intelligently, performs control tasks, and sends commands back to the physical layer

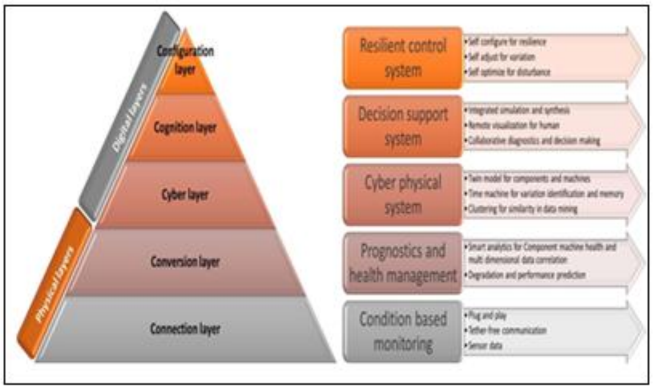

Figure 3: 5C architecture of a CPS

Additive manufacturing (3D printing, 4Dprinting, and 5D printing)

Additive Manufacturing (AM) is a process of creating three-dimensional solid objects by building layers of material based on CAD models. [22] While it was developed in the early 1980s, it gained significant popularity in the last decade with the integration of digital and intelligent technologies in industries. [23]

As mass customization is a key aspect of Industry 4.0, AM plays a crucial role in developing unconventional manufacturing processes, allowing for the production of highly customized, sophisticated products with advanced features that are difficult or impossible to achieve using traditional manufacturing methods.[24]

Over the past few decades, AM technology has advanced to the point where it can produce highly complex, functional parts with tight precision and high aesthetic quality, making it essential in industries like aerospace, biomedical, automotive, manufacturing, and consumer goods. While traditional additive manufacturing is already widely used, current interest is focused on its ability to adapt to new, challenging applications such as printing smart materials, electronics, assemblies, and hydraulic components.

3.9 Challenges of industry 4.0

3.9.1 Unemployment

Studies indicate that major historical events like the Industrial Revolution, the Great Depression, and World Wars have significantly impacted unemployment. While the early industrial revolutions boosted labor demand, leading to urbanization and population concentration, they also contributed to inequalities in rural and urban employment. [25]

During these revolutions, machines and robots helped increase productivity by taking over physical tasks, leaving intellectual work to humans. However, the rise of Industry 4.0 technologies poses a greater threat, as AI can now autonomously solve complex problems, challenging even human intelligence. According to a study by the UN Department of Economic and Social Affairs (DESA), automation could lead to over 80% job loss for low- and medium-skilled workers, while high-skilled workers may benefit from AI. This could worsen wage disparity, and even highly skilled professions like software development, medicine, and architecture may be at risk as AI and robots increasingly take over tasks once thought exclusive to humans. [26]. With the UN projecting a working-age population of 6 billion by 2050, the threat to human employment is expected to grow significantly.

3.9.2 Loss of craftsmanship

Since the 1980s, the competition between human chess masters and computers has attracted more attention from technologists than sports fans, showcasing the effectiveness of AI algorithms. There are numerous instances where AI has outperformed humans in areas like visual recognition, reading comprehension, complex strategy games, and autonomous driving. More recently, AI has demonstrated its abilities by composing original music and even surpassing experienced lawyers in identifying issues in legal contracts. [27]

3.9.3 Wage disparity

The rapid adoption of new technologies in recent decades has significantly widened the wage gap across different labor categories. A World Bank study [28] points out that the labor market has become increasingly polarized, with a growing wage disparity and a steady decline in the income of medium-skilled workers since the 1990s. This shift is partly due to the rise of information technologies and the demand for cognitive jobs, which have boosted wages for high-skilled workers. A study by Acemoglu and Restrepo [29] on automation's impact on the US labor market found that low-skilled workers are most affected by job loss and wage reductions, while high-skilled workers remain largely unaffected. The growing threat of automation and AI has revived discussions around universal basic income, a concept that guarantees a regular income to every adult, regardless of their financial status [30].

3.10 Key takeaways

Industry 4.0 focuses on collecting, processing, monitoring, storing, and analyzing data from various sources in digital form to enhance process efficiency, decision-making, and continuous improvement. Data gathered from sensors connected to physical systems are processed using AI and machine learning algorithms to optimize manufacturing processes, which can also teach the system to improve over time. This detailed data analysis provides a deeper understanding of operations, allowing industries to achieve maximum efficiency.

While Industry 3.0 was about generating data, Industry 4.0 centers on processing and analyzing that data to optimize production and significantly enhance product quality. Although industries can benefit from these digital and computing technologies, high implementation costs and the need for a skilled workforce are obstacles to their widespread adoption. Many businesses remain uncertain about the value of these disruptive technologies, especially given the costs of restructuring and reskilling. However, the more pressing concern is the potential socio-economic impact. If not managed carefully, these technologies could cause significant and irreversible disruptions in society. Therefore, business leaders and policymakers must urgently explore ways to implement these technologies without harming people or communities. The goal is to find methods to integrate humans into the evolving landscape, possibly leading to a new phase of industrial development, like Industry 5.0, which may be necessary to address these challenges

Table 1: Difference between Industry 4.0 and Industry 5.0 technologies

Sr. No.	Industry 4.0 Technologies	Industry 5.0 Technologies
1.	Mass customization	Mass Personalization
2.	Highly automated autonomous system	Individualized human-machine interactions
3.	Automation and Industrial robots	Intelligent automation, collaborative robots
4.	Artificial Intelligence, machine learning	Cognitive computing
5.	Internet of things and industrial internet of things	Internet of Everything, Artificial intelligence of things
6.	Cloud computing	Edge computing, fog computing
7.	Simulations	Digital twins
8.	Centralized traditional database	De-centralized blockchain
9.	LAN, internet	Ultra-low latency, high speed internet
10.	Virtual reality	Extended reality and Metaverse

4. Industry 5.0: Definitions from Industries and Scholars

Many industries that are closely associated with digital technologies have come up with different definitions for the impending fifth industrial revolution. While Industry 4.0 concept itself is yet to get a head start in many developed and emerging economies, these definitions could be considered as a wish list or predictions for the upcoming revolution.

The European Commission defines Industry 5.0 as a vision for industries that goes beyond improving productivity and efficiency. It focuses on placing workers at the center of the production process, with an emphasis on sustainable, human-centric, and resilient research and innovation. [31]. Esben H. Østergaard, CTO of Universal Robots, describes Industry 5.0 as a shift from mass customization enabled by Industry 4.0 technologies to mass personalization, calling it the "human touch" revolution. He predicts a return to pre-industrial manufacturing methods, where humans play a central role rather than being sidelined. This vision emphasizes the importance of reintroducing humans into the manufacturing process to provide personalization and the human touch, supported by collaborative robots (cobots).[32] Nexus Integra, a service provider in Big Data and Industrial IoT platforms defines Industry 5.0 as *"the*

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next step, which involves leveraging the collaboration between increasingly powerful and accurate machinery and the unique creative potential of the human being" [33]

The Global Electronic Services repairs and services define Industry 5.0 as "the revolution in which man and machine reconcile and find ways to work together to improve the means and efficiency of production" [34].

Levity, a service provider in Artificial Intelligence terms Industry 5.0 as something that "adds a personal human touch to the two main pillars of Industry 4.0, automation and eficiency. It refers to people working alongside robots, smart machines, and technologies." They have also pointed out that the core element of Industry 5.0 would be the per- sonal touch which cannot be provided by technologies [35]. Frost & Sullivan calls Industry 5.0 as "a model of the next level of industrialization characterized by the return of manpower to factories, distributed production, intelligent *supply chains, and hyper customization, all aimed to deliver a tailored customer experience time after time"* [36].

Association for Advancing Automation has predicted that the need for greater customization and personalization would drive the fifth industrial revolution that would revolve around a larger collaboration between machines and humans to realize the dual benefits of cognitive computing and human intelligence [37].

Andreas Eschbach, founder, and CEO of a software solutions provider says that Industry 5.0 would be an evolution in the manufacturing process in which humans are assisted by machines to realize the dual benefits of accuracy and cognitive skills [38].

Neil Sharp of JJS manufacturing, a manufacturing solution provider has stated that human-centric development, sustainability, and resilience would be the three pillars of the fifth industrial revolution which aims to empower humans and not replace them [39].

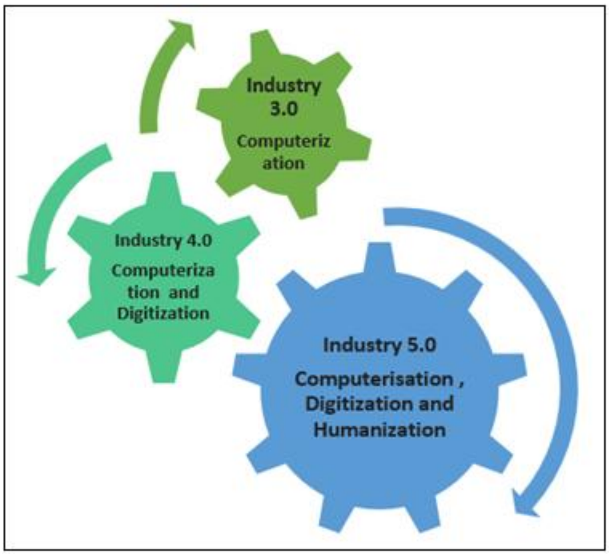

Figure 4: The key differential factors of Industry 3.0 Vs 4.0 Vs 5.0

Eric Howard of Simio LLC, a simulation software provider has also indicated that combining human capabilities and automation to meet the demand for personalization would be the driver of the next industrial revolution [40][41]

Ozdemir and Hekim [147] proposed Industry 5.0 to be a much-required evolutionary and incremental development that is built on the concept and practices of Industry 4.0.

So far, every industrial revolution had attempted either to eliminate or alienate humans who stand to lose against the superior productivity and efficiency of automation and digital technologies. However, for the first time, most of the definitions have confirmed the inclusion of humans and sustainability as the additional key pillars of the fifth indus- trial revolution. Even at the heart of Japan's "Society 5.0" model, they strive to create a human-centered revolution to attain economic development by integrating physical and cyberspace [42,43].

4.1 Prospective Technologies and Applications of Industry 5.0

Industry 4.0 primarily focused on increasing profits through enhanced product quality and process efficiency using digital technologies, but it largely overlooked the role of human intelligence and the environmental and social impacts of these technologies.[44] In contrast, Industry 5.0 is expected to address these gaps by incorporating humans and promoting sustainable development. It will also offer the flexibility and agility needed to quickly adapt to changing market demands and customer preferences. While many industrial leaders and scholars see human creativity as the defining feature of Industry 5.0, some argue it will simply be an evolution of Industry 4.0 technologies and practices. [45,46]

Despite being seen as a gradual progression, discussions on Industry 5.0's enabling technologies and applications are accelerating. The combination of the precision and efficiency of digital technologies with human creativity will create a powerful synergy between humans and machines. Additionally, the increasing demand for highly personalized products is expected to be a major advantage of Industry 5.0, which will leverage AI, machine learning, and additive manufacturing. While previous industrial revolutions focused on mass production, Industry 5.0 is predicted to drive mass personalization, as "one size does not fit all."

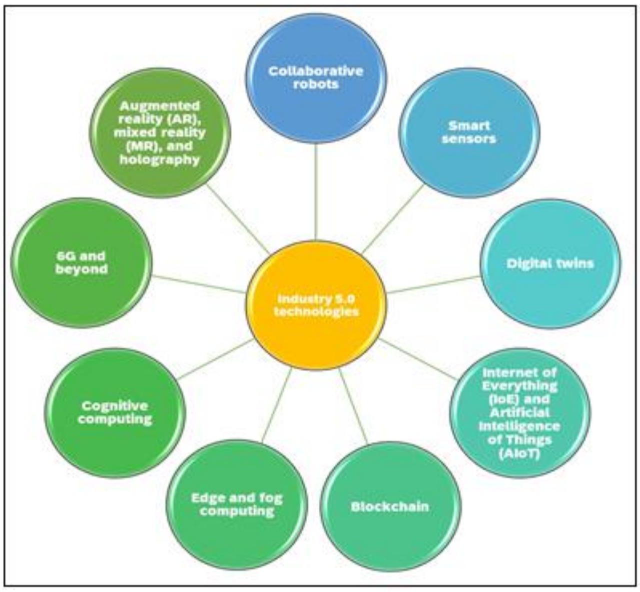

Figure 5: The prospective technologies of Industry 5.0

a) Collaborative robots (cobots)

Robots have been used in industries for decades, but with the fourth industrial revolution, robots are designed to work autonomously without human supervision and already play an active role in many factories. In contrast, robots of the fifth industrial generation are expected to collaborate with humans, guided by them. This shift is driven by advances in digital technologies like artificial intelligence, machine learning, and traditional robotics, leading to the rise of "cobots" (collaborative robots). Cobots are flexible, adaptive, and capable of learning in real-time, making them ideal for manufacturing small batches and personalized products, which are key for future manufacturing needs.[47]

Recent technological advancements like distributed AI, edge computing, and parallel processing enable cobots to make real-time decisions, improving productivity and efficiency. For instance, a cobot in an Indian automotive part manufacturing company improved product quality by 20%, while a cobot in a German company significantly reduced welding time. Cobots are benefiting industries like biomedical, agriculture, food processing, and logistics. However, concerns about safety, trust, job displacement, and the loss of human interaction in the workplace need to be addressed for broader adoption.[48]

b) Smart sensors

A sensor is an electronic device that detects changes in physical properties and converts them into electrical signals. For example, a thermocouple sensor generates a voltage in response to temperature changes. Unlike traditional sensors, which only detect changes, smart sensors can perform data collection, conversion, processing, and communicate with external systems like cloud servers. These advanced capabilities are enabled by integrating sensing elements, microprocessors, communication modules, and memory within a single system. Smart sensors and actuators play a key role in IoT, CPS, automation, robotics, and other intelligent systems, driving the technologies behind Industry 4.0 and Industry 5.0. Thus, their functionality and significance are crucial to modern industrial advancements.

c) Digital twins

Digital twins are accurate digital replicas of physical systems that serve as their virtual counterparts. The core concept involves using data from the original system to mirror its behavior in a digital model for real-time simulation and analysis.[49]

The idea of "twins" dates back to the 1960s when NASA used identical spacecraft to simulate the conditions of a space mission. However, with modern digital technologies, this concept has evolved to create digital models rather than physical ones. NASA first coined the term "digital twins" in 2010 to describe a system integrating simulations with sensor data. Digital twins help prevent system failures and extend the life of physical systems by suggesting optimizations. Unlike traditional simulations, digital twins can simultaneously run and analyze multiple processes.[50]

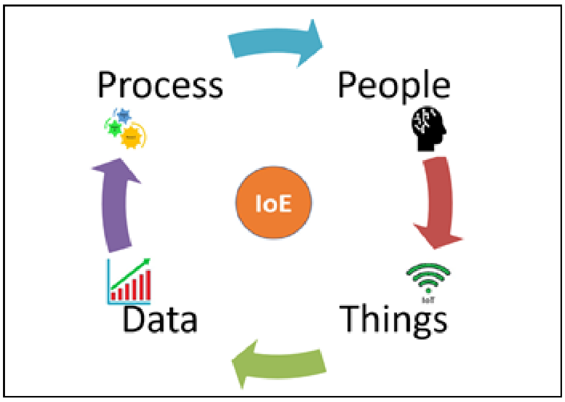

Figure 1: Ideology of IoE: Data based decision, new capabilities and rich experience

d) Internet of everything (IoE) and artificial intelligence of things (AIoT)

The term "Internet of Everything" (IoE), coined by Cisco, describes the interconnectedness of people, devices, data, and processes. Unlike the Internet of Things (IoT), which focuses on connecting physical objects to the internet, IoE encompasses multiple technological transitions, with IoT being one part. IoE's philosophy revolves around connecting billions of devices and objects globally with sensors to enhance networking capabilities and intelligence. Data from devices like smartphones, wearables, and smart appliances are processed by AI algorithms to provide personalized experiences. Cisco estimates that the real benefits of IoE will emerge once 99.4% of currently unconnected objects are integrated.[51]

AIoT (Artificial Intelligence of Things) is the convergence of IoT and AI, enabling devices to make decisions and solve problems without human intervention. By embedding AI algorithms in IoT devices, these systems can analyze vast amounts of data and optimize their functionality autonomously. While the technology is still developing, AIoT is already being applied in sectors like consumer goods, industrial automation, smart health tracking, smart homes, and autonomous vehicles.

e) Blockchain

Blockchain is a decentralized, distributed digital ledger used to store transactions involving both tangible and intangible assets in an immutable format. Its key features, such as trust, transparency, and traceability, make it ideal for applications involving secure transactions. [51]

Each "block" records transactions, and new transactions are added sequentially, ensuring that data is permanently encrypted and tamper-proof. Blockchain provides secure, faster, and accurate data flow between approved members, making it especially useful for business networks. Initially created for the banking sector, it is now seen as a transformative technology for secure data sharing across various industries.[52]

When combined with other technologies like the Internet of Things (IoT), cloud computing, and Big Data, Blockchain can revolutionize data management in industrial sectors. Since IoT is currently vulnerable to security threats due to its centralized architecture, Blockchain can provide enhanced security through encrypted and private data transfer. It also enables decentralized peer-to-peer transactions, automated processes, smart contracts, and the prevention of counterfeiting. [53,54] As Blockchain technology is still emerging in industries, ongoing research focuses on optimizing block sizes and reducing transaction latency to ensure sustainability and efficiency.

f) 6G and beyond

To create a fully connected digital world, advancements in digital, computing, and communication technologies are essential. While next-gen 5G is on the horizon, telecom companies are already researching the technologies needed for 6G, which is expected to be commercially available by 2030. 6G will address the growing need for wireless connectivity for intelligent devices and services. With the ability to use higher frequencies than 5G, it promises higher capacity and lower latency. Though the commercial launch of 6G is still a decade away, its anticipated features include data rates of up to 1 Tbps, wide bandwidths, ultra-low latency, improved energy efficiency, and high reliability.[55]

6G is expected to support various applications such as AI-based autonomous supply chains, e-health, collaborative robots, massive digital twins, and holographic telepresence. With the increasing number of connected devices and vast data generation for Industry 5.0, 6G will also play a critical role in optimizing energy consumption for sustainable use.[56]

5. Conclusion

Industry 4.0 represents a transformative era where advanced digital technologies are integrated with industrial machines and processes to collect data and optimize operations, reducing costs and improving efficiency. This revolution connects machines and systems, automating the entire supply chain from raw material procurement to product delivery. While Industry 3.0 focused on computerization, Industry 4.0 emphasizes making physical systems smarter and autonomous. However, this focus on process efficiency and product quality often overlooks the role of human intelligence, as well as the potential environmental and societal impacts, including job loss and social inequality.

As experts envision the future of Industry 5.0, there is a clear shift toward reintroducing human collaboration with digital technologies, emphasizing personalized products, and fostering a balance between technological advancements and human creativity. Industry 5.0 is expected to prioritize sustainability—social, economic, and environmental—while maintaining agility to adapt to changing market needs. The previous industrial revolutions took significant time to unfold, and the current technological advancements, though revolutionary, still require careful consideration regarding their impact on society and the environment. Rather than calling the next phase "Industry 5.0," some experts propose the term "Industry 4.0S" or "Sustainable Industry 4.0," as the focus will likely be on creating a more inclusive and sustainable future. However, given the ongoing adoption of Industry 4.0 technologies in larger corporations and their gradual implementation in smaller enterprises and developing countries, it is premature to fully define what the next transformation will entail.

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