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A REVIEW OF THE STATE OF THE ART ON THE OPPORTUNITIES, CHALLENGES, AND FUTURE DIRECTIONS OF SMART MANUFACTURING

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Abstract

Utilizing connected machinery and tools to improve manufacturing performance and optimize energy and labor required by the application of big data processing, artificial intelligence, and advanced robotics technology, as well as their interconnectivity, is known as smart manufacturing technology. This paper describes and discusses the smart manufacturing system, including its current implementation status, analyzes the differences between the current and anticipated future manufacturing systems, and talks about related technologies and how they contribute to smart manufacturing technology. In order to fully actualize this quickly evolving technology and address all of its aspects, a study of the most recent advancements in the field was conducted, and its effects, as well as implementation obstacles, possibilities, and future directions for smart manufacturing, were studied and presented.

1. Introduction

Industries are the msain drivers of the national economy and the prosperity of nation and their better performance and high-efficiency yields a better economy. The newly developed manufacturing industries are deploying more intelligent and smart technologies and the produc- tivity of their system has found to be increased by 17-20% [1] with im- proved machine utilization and optimization of energy usage by smart manufacturing systems.

Manufacturers are competing in innovativeness, short response time to change in markets, low cost and reliable prod- ucts to meet the end consumer demands and this competition finally lead to the smart manufacturing, digitization of the process and the cyber-physical control in manufacturing plants to the business outlets [2,3].

The manufacturing system involving the smart devices and sen- sors for manufacturing goods with less human interventions, customized manufacturing instructions can be obtained directly from end customers through the use of internet in manufacturing [4–7]. Most of the coun- tries have already introduced their policies of cyber-physical systems and digital manufacturing for the advancement of future manufactur- ing. Germany has announced the fourth industrial revolution named as'Industry 4.0' (I4.0) which basically uses the interconnected machining systems which interacts themselves for the production planning, plant scheduling, product customization, flexible manufacturing, faults iden-tification and recovery [8]. The concept of I4.0 can be seen as the in- tegral form of Internet of Things (IoT), Cyber-Physical Systems (CPS), digtal manufacturing, smart manufacturing technologies, additive man- ufacturing, 5G mobile communications, robotics technologies, big data processing, data analytics, system integration, simulation and Flexible Manufacturing Systems (FMS) [9-15]. China has also announced their 2025 plan named as "Made in China 2025" and internet plus program to boost the manufacturing industries to the next level [6,16-19]. The evolving distributed manufacturing systems by replacement of classi- cal hierarchical control modes are very essential to realize the smart manufacturing system which would be able to address the increasing customization, sudden supply-chain fluctuations and also, suitable for smaller production lots [20,21]. According to McKinsey Global Insti- tute's report, the manufacturing industry has 60% of automation poten-tial, which also indicates that smart manufacturing technologies can be implemented to the industries to boost their capacities [22].

The schematic layout of interconnection of smart manufacturing sys- tem used in industry4.0 is shown in **Figure 1**. The smart manufacturing system connects the product design, analytics, manufacturing process, stocks and supply chain system, product customization, real-time ma- chining units, product delivery system and the end customers through the use of cloud computing which made on-demand manufacturing, product customization and maintain the demand and supply ecosystemmore efficient [23].

Moving towards the smart manufacturing technologies, some of the leading countries which have a great impact on the global market have already declared their initiatives for the next generation industries. In- dustry 4.0 is an initiation of Germany, which has been accepted to many

Figure 1. A schematic of smart manufacturing components [24].

Table 1
Strategies declared by different countries for the next industrial development.

Country	Declared Strategy
Germany	Industry 4.0 [9]
China	Made in China 2025 [16]
Japan	Society 5.0 [25]
United States	Industrial Internet Consortium [26]

nations as the next-generation technology for revolution in industrial sector. The emerging strategies declared by the different countries are listed in Table 1.

This study briefly explains the scope and necessity of smart manufacturing systems and the future directions of the smart manufactur- ing system in different aspects. It is focused on discussing current practices in manufacturing systems and their innovation in different areas, application of cyber-physical systems and interconnected devices and their impacts in smart manufacturing. This paper firstly introduces the smart manufacturing systems and their importance in application areas. The second section explains the background, historical developments ofmanufacturing and control system, and discusses the components con- tributing to smart manufacturing systems. Third section of paper high- lights the technologies related to smart manufacturing and automation system and their scope in detail. Section 4 discusses the standardiza- tions related to smart manufacturing technology, Section 5 highlights the challenges of implementation of smart manufacturing systems and in Section 6 the future opportunities of smart manufacturing technologies are discussed. Finally, in Section 7 conclusions are drawn and presented.

2. Historical Background of Manufacturing

From the early age machining process to today's automated manu- facturing industries, the manufacturing industries have achieved huge advancements. Going through various inventions and repetitive trials over the years, manufacturing and industrialization systems are now reached their fourth generation of the industrial revolution. During this period, there have been several improvements and changes as far. The timeline in **Figure 2** shows the different ages of the industrial revolution highlighting major achievements/inventions which are identical to be the newer revolution.

2.1. Industrial Revolutions

(a) First Industrial Revolution

The first country in the world to begin industrialization is the United Kingdom, which began the development of the cotton industry from a worker based cottage industry into the machine-based economy in the first half of the 18th century [27]. With this beginning to the new man- ufacturing process, the period between about 1760 to 1820 is known for the first industrial revolution in Europe and America. In this period, textile industries were the large industries in terms of capital invest- ment, output and the number of employments offered and also the first industry to use modern production technologies [28, 29]. The discov- ery of the spinning jenny (which produced multiple spools of threads at once) in 1764 by James Hargreaves boosted the generation of machin- ing and invention of coal, the iron, railroads and textiles were the key

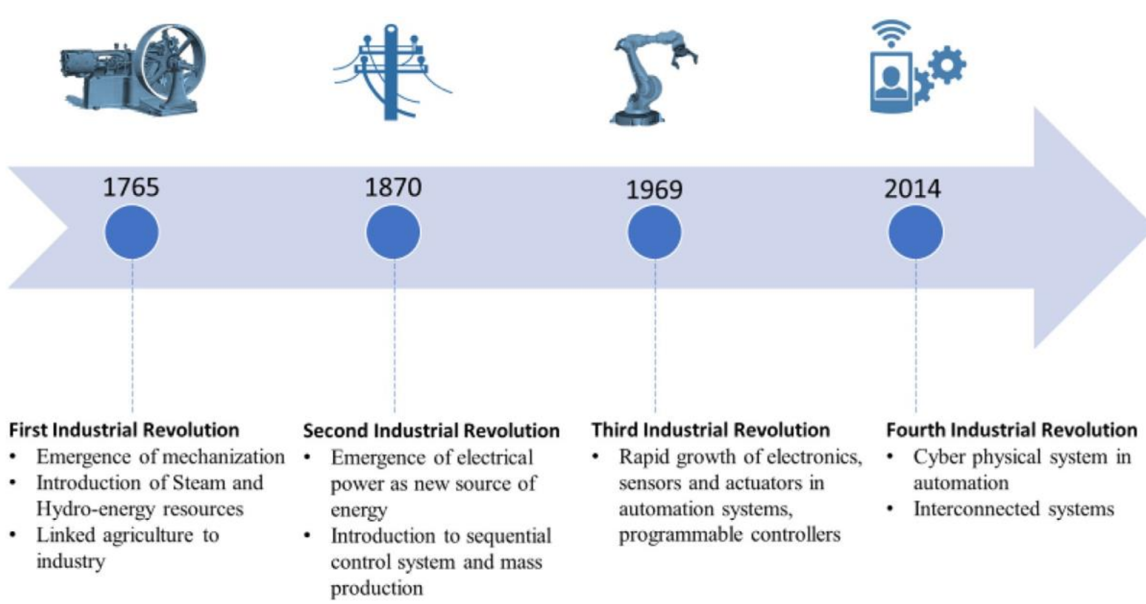

Figure 2. Chronology of Industrial Revolution.

Table 2
Developments in Control System [35-38].

Year	Achievements
1769	James Watt's steam engine and governor developed. The watt steam engine is often used to mark the beginning of the industrial revolution
1771	Richard Arkwright invented the first fully automated spinning mill driven by water power
1800	Eli Whitney's concept of interchangeable parts manufacturing in the production of muskets. It is considered to be the beginning of mass production
1868	J C Maxwell formulated the mathematical model for governor control of a steam engine
1913	Henry Ford's mechanized assembly machine introduced for automobile production
1927	H.S. Black conceives of the negative feedback amplifier and H.W. Bode analyzes feedback amplifiers
1932	H. Nyquist develops a method for analyzing the stability of systems
1941	Creation of first anti-craft gun with active control
1952	Numerical Control (NC) developed at Massachusetts Institute of Technology for control of machine tool axes
1954	George developed 'programmed article transfer', considered to be the first industrial robot design
1957	Sputnik launches the space age leading in time to miniaturization of computers and advances in automatic control theory
1960	The first Unimate robot introduced, based on Devol's designs. Unimate installed in 1961 for tending die-casting machines
1970	State-variable models and optimal control developed
1980	Robust control system design widely studied
1983	Introduction of the personal computer (and control design software soon thereafter) brought the tools of design to the engineer's desktop
1990	Export-oriented manufacturing companies emphasize automation
1994	Feedback control widely used in automobiles. Reliable, robust systems demanded in manufacturing
1997	First-ever autonomous rover vehicle, known as Sojourner, explores the Martian surface
1998-2003	Advances in micro- and nanotechnology. First intelligent micromachines are developed and functioning nanomachines are created
2003-present	Cyber-physical control systems featuring artificial intelligence technology are rapidly growing

developments in the first industrial revolution. It is time when mecha- nization commenced, a process that replaced agriculture with industry as the foundations of the economic structure of society. Mass extractionof coal along with the invention of the steam engine created a new type of energy that thrusted forward all processes thanks to the development of railroads and the acceleration of economic, human and material ex- changes.

(b) Second Industrial Revolution

The time between 1830 to 1914 is the period of the second indus- trial revolution and is also known as technological revolution [30]. New technological advancements initiated the emergence of a new source of energy: electricity, gas and oil which give rise to the different inven- tions. As a result, the development of the combustion engine set out to use these new resources to their full potential. Furthermore, the steel industry began to develop and grow alongside the exponential demands for steel. Chemical synthesis also developed to bring us synthetic fabric, dyes and fertilizer. Methods of communication were also revolutionized with the invention of the telegraph and the telephone and so were trans- portation methods with the emergence of the automobile and the plane at the beginning of the 20th century [29]. All these inventions were made possible by centralizing research and capital structured around an eco- nomic and industrial model based on new "large factories". Chemistry also began its road toward the supply of new artificial materials like Disinfectants and antiseptics, particularly phenol and bromines, role of microbes in the infection of wounds, salicylic acid etc. Electric genera- tors, vacuum pumps, gas lighting systems, transformer are the electric systems developed during this revolution. Electricity was recognized to be a general system of energy transmission. Railways have compara- tively become faster, diesel engines, clipper ships were developed in the field of automobiles. Steel implements, drainage- and irrigation pipes, steam-operated threshers, seed drills, and mechanical reapers were some contributions in the field of agriculture. By changing the relationship be-tween knowledge of nature and how it affected technological practices, it irreversibly changed the way technological change itself occurs.

(c) Third Industrial Revolution

The world economy and the development were also affected by the world war I and II and the industrial developments were again resumed after the second world war and the time period after 1969 is called as the third industrial revolution. The electromechanical systems were upgraded into computer-based control systems, where Programmable Logic Controllers (PLC) and industrial robots were the great inventions and implementation in the industrial automation system [31, 32]. The third industrial revolution appeared with the emergence of a new type of energy whose potential surpassed its predecessors i.e. Nuclear en- ergy. This revolution witnessed the growth of the transistor and micro- processors but also the rise of telecommunications and computers. Thisnew technology led to the production of miniaturized material which would open doors, most notably to space research and biotechnology. The third revolution used electronics and information technology to au-tomate production.

(d) Fourth Industrial Revolution

In 2011, a group of business politics and academic experts intro- duced the term Industry 4.0 as the fourth industrial revolution to enhance the German competitiveness in the manufacturing industry [33,34]. which focuses heavily on interconnectivity through IoT, ma- chine learning and focuses more on the processing of real-time data. Industry 4.0 connects internet of things and industrial internet to the manufacturing system to interact with the machines to share their in- formation and make intelligent decisions based on the system algorithm. Industry 4.0 basically includes artificial intelligence, automated robots, flexible manufacturing automation systems, additive manufacturing and augmented reality [29]. Migrating to I4.0 is a gradual process and takes time to upgrade everything from the existing system. Physical infrastruc- tures, adoption of new technologies, being familiar with it and availabil- ity of technical manpower are necessary to be upgraded into the modernsystems.

2.2. Developments in Control Systems

Throughout various practices on making different controllers or tools to regulate the system performance in desired manner. In the past, most of the controllers were mechanical systems operating based on the classes of levers, pulleys and gravitational forces to take any action to the ongoing process. Gradually, fully mechanized controllers were replaced by the sequential circuits of switches and electromechanical relays and then by the digital electronics and intelligent control sys- tems. **Table 2** summarizes the major inventions in the control systems from its evolution to the present scenario.

2.3. Technologies associated with Smart Manufacturing

Smart manufacturing integrates various technologies related to man- ufacturing, computing, virtualization, connectivity, data handling etc.

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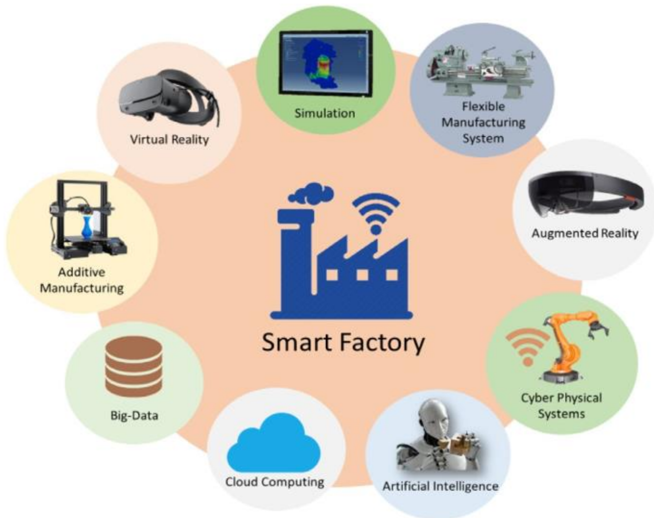

Figure 3. Components of Smart Manufacturing System.

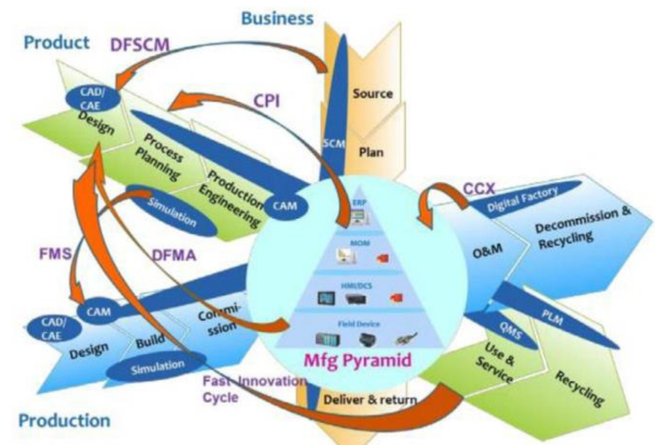

Figure 4. NIST's smart manufacturing eco-system model [20].

The scope of smart manufacturing technologies has become broader due to the inter-operation of various technologies resulting in cost- effectiveness, time-saving, easy configuration, better understanding, quick response to market demand, flexibility and remote monitoring. Figure 3 illustrates the baseline of the smart manufacturing system and their roles in the smart manufacturing system are presented in Table 3.

3. Overview of the System

The interest of process automation evolves from minimizing human interference in the systems to avoid health hazards and to increase pro- ductivity. Automation in the manufacturing industry has evolved from the use of basic hydraulic and pneumatic systems to today's modern robots [64-66]. The benefits of automation include increased produc- tivity and quality, improved accuracy, saving material costs and energy [6,67]. Going through the technological transformations from the past, the wireless-based automation system is being adopted in the different types of system and the use of IoT in them is to ease their operation.

The use of internet in the control systems is being introduced for the added benefits of remote sensing, distance control, easier data ac- quisition systems and flexibility of the automation system adopted in the industries as well as in power and energy systems [50,68,69]. IoTis being a topic with a wide scope and emerging technologies, it can be implemented in various systems to make the system operation eas- ier and less human intervention in the automated control system with global networking infrastructure. The concept of smart manufacturing system along with micro-grids, smart grids, advanced metering systems, centralized load dispatch and control systems, distribution system au- tomation etc. uses the features of IoT. In the context of power system transmission and distribution, implementation of Smart technology in automation and control is still under research and some of the imple- mentations of such projects can be seen as pilot projects of the utility companies and the local governments.

3.1. Smart Manufacturing System

The Smart Manufacturing System (SMS) is the digitization of every part of the manufacturing system with interoperability, real-time con- trol and monitoring, flexible manufacturing, quick response to the mar- ket changes, advanced sensors and big data analytics with enhanced productivity [6,20]. The SMS operates in two modes; semi-autonomous and fully autonomous. In the semi-autonomous system, the production engineer defines the goals and sets the parameters in the production system. In a fully automatic system, the SMS itself defines the optimal operating parameters and is implemented automatically to all the inter-linked production units [70].

For the manufacturer, the primary concern for standing in the com-petitive market is also building the capacity of cost-effectiveness, opti- mal product manufacturing and delivery time, quality of products and flexibility in product customization [4,71]. The other concern is the abil- ity of any manufacturing system to continuously maintain and improve performance using information and changing environments as chang- ing factors. There are a large number of technologies developed to cre- ate a smart manufacturing system. The technology selection might be one of the big issues to convert an existing system into a smart man- ufacturing system. There are certain strategies to find a smart choice. The Supply Chain Readiness Level, Manufacturing Enterprise Solutions Association (MESA) Manufacturing Transformation Strategy (based in ISA-95 methods) are common strategies used. They don't use the infor-mation and communication as a primary foundation but focus on the single technology or manufacturing execution system. Information and communication technology must be used to evaluate and change to a smart system. [72, 73]

Using information and communication technologies is a clever idea that is illustrated in the industry 4.0 model. The different services at the industry can be converted into smart services linking business pro- cesses with efficient data and process management of the system. Using IoT to bind the system and services can turn the industry into a smart industry. Different data analysis software must be developed with the incorporation of a security system to analyze and secure the incoming data.

Fig. 4 shows the smart manufacturing ecosystem presented by the National Institute of Standards and Technology (NIST), which describes the interrelation of the related domains of smart manufacturing and their functions. This eco-system shows the correlation between the prod- uct (green arrow), production process (blue arrow) and business (orange arrow) of the enterprise and their lifecycle in the schematic presentation. The components of NIST smart manufacturing system shown in Figure4 has been elaborated in Table 4.

Digital transformation and smart technologies that are fusing the physical entities through the internet are now becoming the pillar for next-generation industries. Industry 4.0 by Germany, Made in China 2025 by China, Industrial Internet by the USA, and Society 5.0 by Japan are the major announcements of the leading countries in tech- nology. These technologies are different in the sense of implementation methodology, target group of industry, and the projected timeline for its achievement but have a common objective of implementation of smart and digital technology to boost the current manufacturing systems in the world [17,19,63,74].

Table 3
Technologies and their roles in smart manufacturing.

S.N.	Technology	Contribution in Smart Manufacturing
1	Virtual Reality [22,39–43]	Virtual Reality (VR) provides the facility for experiencing the computer-generated images and videos simulating into real-world activities. VR is a wearable device containing video device, audio device, positioning systems such as GPS, external connectivity to other devices and hardware to make the user experience his physical presence in the virtual environment created in simulation. VR has been used in the manufacturing systems for training the young engineers and technical graduates who are not well-prepared to deal with the industrial processes are introduced to the manufacturing process, mechanization processes, troubleshooting and maintenance systems through the application of VR which have been more beneficial than the theoretical learning. It also helps to reduce the prototyping and testing cost of any product by visualizing the design without making it physically. Also, it helps in the digital manufacturing process to visualize and test the products in a simulated environment for the end customers, which expands more options for product customization, renovation and rapid testing of product design.
2	Augmented Reality [11,44,45]	Artificial environment created across the real-world using computer simulation and can be realized through wearables and mobile devices. They use the technology of combining the real physical environment along with the computer-generated graphics to visualize artificially added components to the existing real-world scenario for training, simulation or validation purpose of some of the manufacturing designs before going for real manufacturing. This integration of simulated computer graphics to real-world scenarios helps to realize the product in an existing environment. Training to new employees and product testing with a demonstration of various conditions in the augmented environment has been found more efficient and time-saving.
3	Cyber-Physical Systems [4,13,46-49]	The industrial processes can be directly monitored and controlled through the use of the internet by the industrial manufacturing engineers, which enables the control engineer to access the control system of the industry from anywhere through cloud computing. Cyber-Physical System (CPS) collaborates the computational entities to the physical world and its ongoing processes utilizing data processing services available directly on the internet. The cloud-based SCADA system can also be defined as the CPS where the sensors, actuators and hardware devices fall under the physical devices and the software, communication system and information exchange through the internet falls under the cyber layer. The major application areas of CPS are implemented in aerospace, automotive, transportation and civil infrastructure.
4	Additive Manufacturing [12,14,43,50–53]	The Additive Manufacturing (AM) also known as 3D printing technology creates new horizons towards smart manufacturing technology. AM technology is flexible for customization, rapid prototyping, making spare parts quickly and on-site manufacturing which also saves huge time of production and cost in machine tools replacements and raw materials. AM also facilitates reverse engineering of any parts or product through 3D scanning and allows reconfiguration in design and quick reproduction for testing and validation is the major contribution of AM in smart manufacturing. AM technology is also being widely used in medical science for implants in dentistry and orthopedics for the replacement of injured body parts. In civil and architectural engineering, AM is utilized in prototyping and design testing of structures for cost-effectiveness and customer satisfaction.
5	Big Data Analytics [43,47,54–56]	The collection and analysis of data from various sources like production unit, enterprise, customer feedback and product request system, etc. help in real-time decision making for smart manufacturing. Today's manufacturers want their customers to share their feedback and personal view in the products they are using or intend to use, and from that information, manufacturers intend to focus their product design to address the wide range of customers. Big data analysis will benefit the manufacturer in the identification of current state and causes of product failures in real-time, driving the customers to buy their products by understanding their buying habits and requirements, and also, learn the potential of data-driven marketing for predictive manufacturing.
6	Flexible and Reconfigurable Manufacturing Systems (FRMS) [4,57]	Manufacturing system capable of adopting any variations occurred in built-in priority and functions due to the market demand changes or due to reconfiguration of product. They are focused on cost-effectiveness and quick response to rapid system changes. It is capable of production in small batch size and easily reconfigured for manufacture different variety of products which can be divided into two types; routine flexibility allows the manufacturing plant to produce new types of product in the same production line while machine flexibility allows to schedule the manufacturing routines of different machining stations, share the machining activity between them, replace the machining parts automatically. The deterministic characteristics of FRMS in smart manufacturingare modularity, integrability, flexibility, scalability and diagnosability.
7	Artificial Intelligence [46,58,59]	For better human-robot collaboration and reduce the human workforce in risk zones, to improve the maintenance system of the manufacturing system and detection of any failures in the machinery and the product, artificial intelligence is adapted in new generation manufacturing system. The artificial intelligence system is capable of self-decision, self-optimizing and automatic response to physical changes such as changing the production schedules, stopping or running of any machining units, machine tools automatic replacement and warning of any uncontrollable situations in time.
8	IoT and IIoT [5,15,48–51,60]	IoT is being used in common domestic applications like smart homes, transportation, logistics, healthcare, agriculture, human pets and vehicle tracking applications and IIoT is focused on the Industrial application of IoT connecting every physical entity with each other through the internet. In industries, the IIoT connects the physical entities like sensors, actuators and the entire process monitoring and control system into the internet cloud, enabling the interaction and cooperation of each entity together to reach the common goals. These interactions between each component help in production planning, predictive maintenance and faults localization, better human-machine interaction, intelligent process control for resource, tools and materials optimization. IIoT also allows the digital presentations of products, processes and factories to the customers for marketing and informative purposes too.
9	Simulation [46,61–63]	Simulation of plant operations to optimize the machine settings for preceding production line in a virtual environment without testing in physical world would save time and money in testing the production system. Simulations are used to mirror the physical world in a virtual model which can be used for production planning and scheduling according to obtained simulation results. Moreover, simulation has been implemented in SMS system these days which helped to analyze the design errors, production time, workforce and energy required for the entire production and facilitated the preparation of cost estimation, profit loss analysis, preparation of bill of quantity before proceeding into real manufacturing process.

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Components related to NIST's smart manufacturing ecosystem.

Components	Description
PLM (Product Lifecycle Management)	Managing entire lifecycle of the product from inception through design and manufacture to the disposal
SCM (Supply Chain Management)	Management of the flow of materials, final products and related information within suppliers, resellers and end customers
DFSCM (Design for Supply Chain Management)	Designing products to take advantage of and strengthen supply chain
CPI (Continuous Process Improvement)	An ongoing process involving engineering and management system redesign and optimization occurs
CCX (Continuous Commissioning)	An ongoing process of diagnosis, prognosis and performance improvement of production systems
DFMA (Design for Manufacturing and Assembly)	The design for ease of manufacture of the parts and design for easy assembly of the product
FMS/RMS (Flexible/Reconfigurable Manufacturing System)	Flexible machining for reconfigurable production types without changing the entire process
Manufacturing Pyramid	The hierarchical structure of an existing manufacturing system
Fast Innovation Cycle	To improve new product Introduction cycle by anticipating trends through gathering data from product usage and feeding it back into product ideation

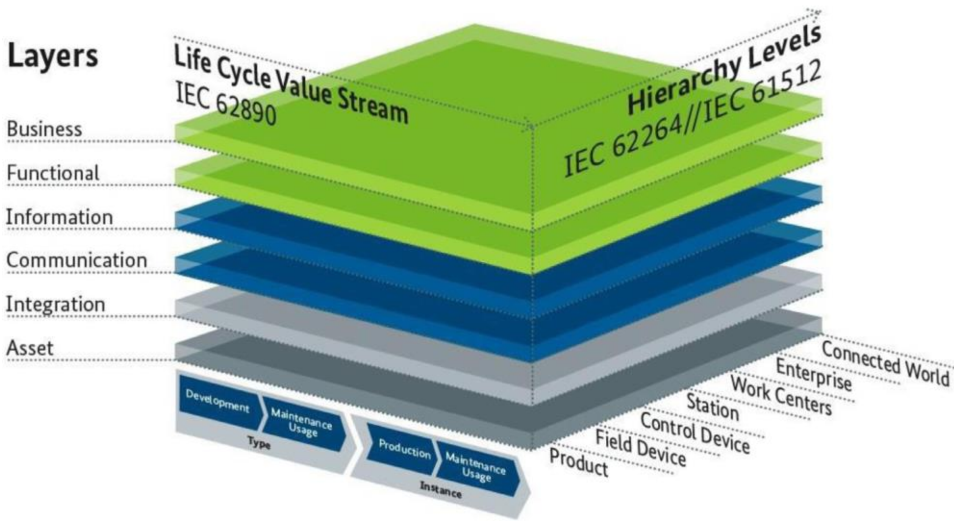

Figure 5. Reference Architecture Model for In-dustry 4.0 (RAMI4.0) [79].

As the name suggests, Industry 4.0 is the digital transformation spe-cially focused for next level of industrial revolution declared by Ger- many in 2011 which has defined six fields of priority; digital economy and society, the sustainable economy and society, the innovative work- place, healthy living, intelligent mobility and civil security [34,75-77]. As I4.0 is targeted to combine manufacturing technology with informa-tion technology and service sectors, its performance is highly affected by the reliable internet connectivity and efficient algorithms [45,73,77]. I4.0 targets to utilize the IoT in the manufacturing industry to enhance the supply chain and focuses on competition to produce high value- added products and distribution of the modules and machine tools re- quired for manufacturing all over the world [78].

The RAMI4.0 illustrated in **Figure 5** shows three dimensional be- tween the layers, life cycle stream and the hierarchy levels in I4.0 en- vironment [79]. This shows the relationship of every components of I4.0 in comprehensive presentation. Asset, Integration, Communication, information, functional and business characters of industry are listed under layers category. Similarly, product, field device, control device, station, work centers, enterprise and connected world falls under the hierarchy levels which defines how the information and workflow takes place in I4.0. the development and maintenance system are categorized under life cycle value stream in the RAMI4.0 reference model.

Made in china 2025 was introduced in 2015, targeting to grow china's industrial market as the manufacturing hub for the global mar- ket. Made in China 2025 is also inspired by the industry 4.0 revolution initiated by Germany and is specially targeted for the implementation of digital manufacturing technologies to compete with the global industrial market [80]. Manufacturing history in china has three basic periods. The initial period was Incubation years until 1991 in which the structural ref- ormation and special economic zones were established and private firms were allowed to participate in manufacturing and production business. The next period was Navigation period until 2001 and most of the in- frastructural developments, financial special zones were established and access to WTO was also achieved in 2001. The recent age of manufactur-ing and industrialization falls under Dynamic year and is now focused in development of global manufacturing supply chain and established china as a leading country in the world in manufacturing and also be- came world's 2nd largest economy in the world. Made in China aims to replace the foreign technology with all the Chinese technology and be- come the leading manufacturer in the world targeting to produce 40% of mobile phone chips, 70% of industrial robots and 80% of renewable energy equipment of the world population in China by 2025 [81]. But still now, most of the Chinese industries are lacking automation tech- nology and are mostly dependent on labor-oriented manufacturing and Made in China 2025 aims to implement more automated technology intheir manufacturing systems and migrate into the theme of smart man-ufacturing technology with in the year of 2025.

Society 5.0 was launched in January 2016 [82] and was identified asone of the growth strategy for Japan and this concept is also known as asuper-smart society. Society 5.0 was initiated as the political agenda in Japan addressing the 12 different service platforms for creating a super smart society includes smart manufacturing systems, smart food chain systems, intelligent transportation systems, energy value chains, new manufacturing systems, regional inclusive care systems, infrastructure maintenance and updates, society resilient against natural disasters, new business and services, hospitality systems, global environment informa-

Table 5
Characteristics of newly introduced smart technologies.

Originating Country	Industry 4.0 Germany	Made in China 2025 China	Society 5.0 Japan	Industrial Internet USA
Focus area	SME Worldwide	Industries of China	Smart Society primarily in Japan and rest of the world	Industries worldwide
Major Contribution to the field	Digitization of manufacturing industries worldwide	Making China as leading country in manufacturing in the world	Digitization of society in 12 major fields	Digitization of Industries through internet
Introduced	2011	2015	2016	2012
Base Technology	Internet and Interconnected devices	Internet and Interconnected devices	Internet and Interconnected devices	Internet and Interconnected devices

Table 6
Design Considerations for IoT in industries [67, 90].

Goals	EXplanation
Energy	Operational limitations for limited power supply
Latency	The time required for information exchange
Throughput	A maximum amount of data that can be transported through the system
Scalability	Number of maximum supported devices
Topology	The communication chain, which communicates to which node
Security and Safety	The level of security in the system

tion platform, integrated material development systems [83]. Society 5.0 is the fifth version of "new society" going through the hunting so- ciety, the agrarian society, the industrial society and the information society in the past [84]. The technological background of Society 5.0 is the integration of Cyber-Physical System (CPS) with Information and Computer Technology (ICT) in the background and the value creation of this technology would be boosted by AI robots based in CPS [78, 85]. Society 5.0 originated in Japan and is targeted its implementation to contribute the world.

Industrial Internet Platform (IIP) was proposed by General Electric in the USA as Software as a Service model, and is now the use of inter- net in the industry is being expanded for internet integrated production and control mechanism [78]. The IIP manages the interaction between the physical components and the cyber components of the industry. The current IIP is mainly concerned about the maintenance of intelli- gent products and fault detection and localization [49]. Wang et. al. [49] also proposes the Ind-OS as the Industrial Operating System for su- pervision of manufacturing system through IIP, which integrates the En- terprise Resource Planning (ERP), Enterprise Information Systems (EIS), Human Resource Management (HRM), Customer Relation Management (CRM) and Manufacturing Executive System (MES). The industrial in- ternet covers the 5C architecture in which Connection layer is located in the base layer for condition monitoring, second layer is conversion layer for translation of data from connection layer into the information which would be utilized by the cyber layer in third layer. The information form cyber layer is utilized by technicians in cognition layer and is supervised by configure layer by the decision makers based on the information and interpretation by the technicians [86]. The comparative table showing the relations between these emerging technologies has been shown in Table 5.

3.2. Application of IoT in Process Industries

The use of IoT has been adopted widely in the field of industrial automation in developed countries. Automatic Guided Vehicles (AGVs) are used for the purpose of unmanned transportation especially for mov- ing goods from one location to another with self-loading and unloading capacity. AVG follows the lines on the floor or uses vision cameras, ra- dio waves or laser for navigation [87]. AGVs are also used in cleaning, assistance to deliver peoples, etc. and they can be centrally controlled from the cloud-based server [88]. As the technological revolution in the industrial automation systems, industry 4.0 has been introduced as the generation of robotic industrial automation system which is also termed as the cyber-physical system or the IoT [89].

The architecture of IoT is basically divided into 4 layers. The first layer includes sensors and actuators which are integrated into hardware to collect the information from them. After that, the networking layer for the transmission of collected data from sensors to control units and control units to the actuators. To access the services based on user needs and to interact with the control units service layer and interface layer are defined.

The design considerations for IoT in industries has been presented in Table 6 and its working mechanism has been presented in the **Figure 6**. The information from the physical system is collected through the use of sensors and different machine learning tools. These collected informa- tion through the sensors are then managed systematically and processed in the local smart devices/perception devices as shown in the figure, then this information are sent to the application layer through network layer for the implementation in their respective fields. The application layer decides to take necessary action to the IoT integrated system.

The IoT architecture as shown in Figure 6 illustrates the relation- ship between physical system or things that are responsible to interact with the physical entities like temperature, humidity, speed, pressure, velocity etc. through the sensors and respond them through the actua- tors and controllers based on the type of deployment in the system. The IoT is applicable for smart buildings, smart home, smart health, smart transportation, smart industry etc.

In the past, the internet was the medium to connect people through email, social forums and later through social networks. According to Evans [92], Cisco Technology claims that IoT was born between 2008 and 2009 when the number of connected devices exceeded the world population (**Figure *7***) although the term IoT was coined by Kevin Ash- ton, a British technology pioneer in 1999 [93].

Cisco has also presented an example in infographics [94], which describes how things working independently communicate with each other to make valuable results by the use of the internet of things. This demonstrates the alarm of the end-user lets him sleep 5 minutes more by getting information that meeting is postponed for 45 minutes, the train is delayed by 20 minutes and traffic systems that there is accident in road causing to take diversion which takes 15 minutes to reach the train station and alerts coffee maker to turn on 5 minutes later and sig- nals the car to start in 5 minutes to melt the accumulated ice in overnight snow storms. This example clearly explains the working mechanism of systems-of-systems as they were working independently and when they need to work together or make a common decision it can be said to fea-

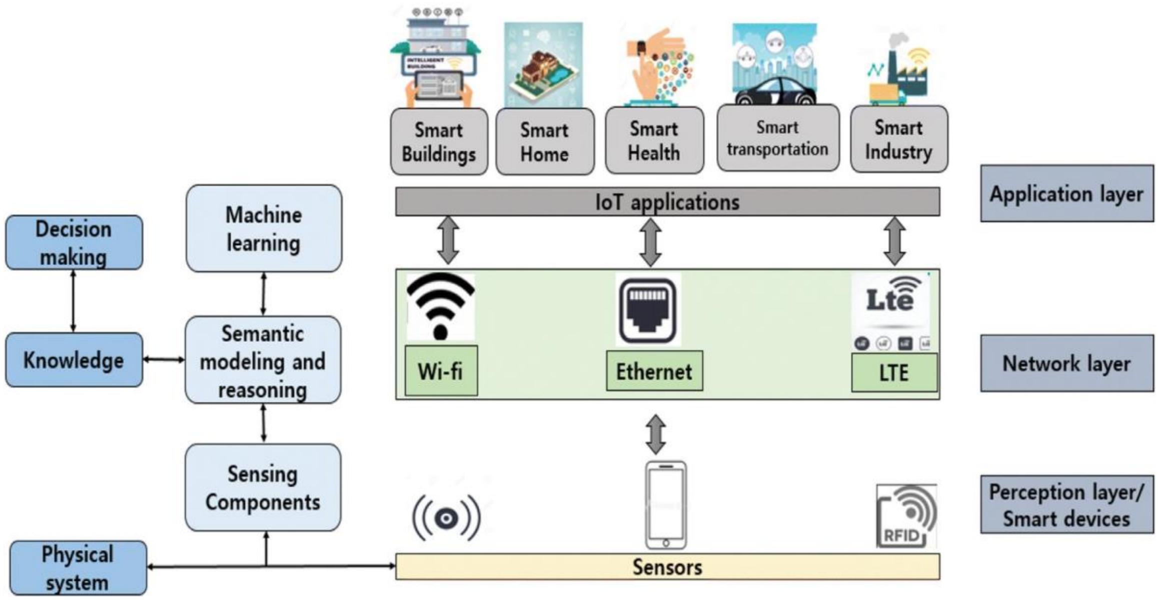

Figure 6. Overview of IoT Architecture [91].

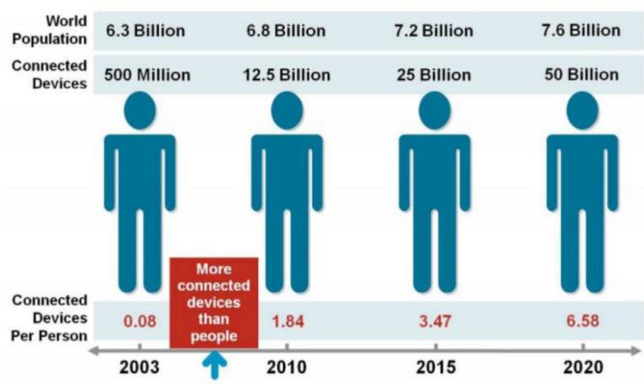

Figure 7. Number of Connected devices per person [92].

ture interoperability between the interconnected devices and systems in the network of IoT. With the expansion of the use of the internet, the number of connected devices per person in 2015 was raised to 3.47 from 0.08 in 2003 and predicted to be 6.58 connected devices per per- son in 2020 [92]. IoT should extend the benefits of the regular internet to physical things by offering stable connectivity, data exchange and remote controllability [95].

3.3. Emergining Smart Technologies in Electrical Power Systems

(a) *Smart Energy Districts*

In the last decade, the interest for distributed generation (DG) has been induced drastically due to technological innovations and a chang- ing economic and regulatory environment [96]. Private small plants, es- pecially from non-dispatchable renewable energy sources, are directly connected to the grid. Power Cloud injects smartness into the man- agement of an energy district so as to improve the global energy ef- ficiency [90]. The article [97] proposes IoT solutions for energy dis- tricts which aims the energy exchange within the various distributed generation plants and local energy storage system to the distribution grid with the goal of improving the energy efficiency and reducing the costs. The geo-referenced energy prediction and generation procedure has also been discussed in [98] and uses the Geographic Information System (GIS) to locate the consumers and based on their categories i.e. residential, industrial or corporate offices.

(b) *Smart Grids*

Smart grid technologies emerged as the consecutive development of electronic control, metering and monitoring and the National Academy of Engineering in the USA has also quoted the electricity grid as one of the major achievements of mankind in the 20th century [99,100]. The smart grid establishes two-way interaction between the consumer and the utility service company where electricity and the information can be exchanged. It is a network of communication, controls, computers, automation, and new technologies and tools working together to make the grid more efficient, more reliable, more secure which also improves

the speed of fault detection and allow self-healing of the network by possible rerouting and switching into another healthy source without human intervention. This will also improve the reliability of electric supply, and reduces vulnerability to natural disasters or attacks [101- 103].

The smart grid can be viewed as the latest upgrade of the pre- existing electrical power systems which allows the dynamic gateways for distributed generations and storages, and smart optimization of en- ergy usage and are charged based on their consumption automatically [99,104]. Smart grids are also referred as intelligent grid or future grid [105,106] and according to the Energy Independence and Security Act of 2007 [107], must include the basic features like fault-tolerant by re- sisting attacks, self-healing capacity, dynamic optimization, improved reliability, power quality, incorporation of demand response and inte- gration of distributed energy sources.

In **Figure 8**, the layout of the smart grid is presented which features the end to end communication of the power system to ensure better performance and reliability. All types of generating stations, transmit- ting and distributing substations, end consumers and the control stations are linked by the internet protocol, which exchanges the information to and from those units. If there is an increase in demand, the generating station increases the active generating units within them and the dis- tributed generating stations which are isolated during low demands are also activated to meet the energy demands. When there are any faults in certain sections, those are isolated automatically and possible rerouting will be accomplished to ensure the power continuity. To save the cost of energy, the scheduling of usage of electrical loads like electric ve-

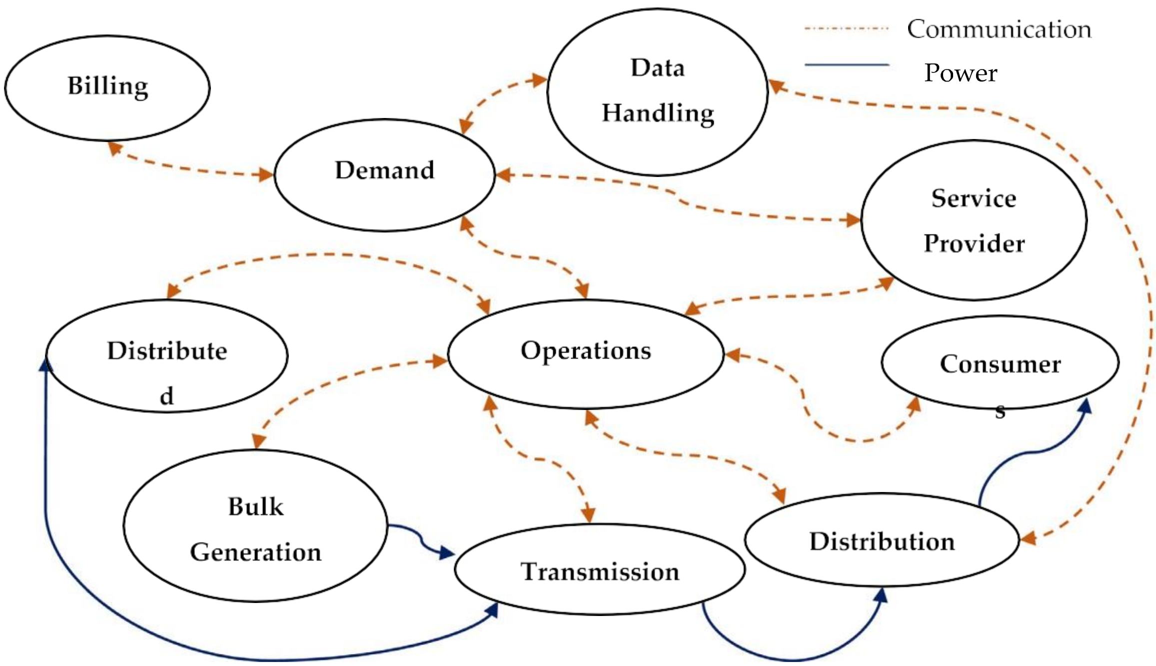

Figure 8. Layout of Smart Grid.

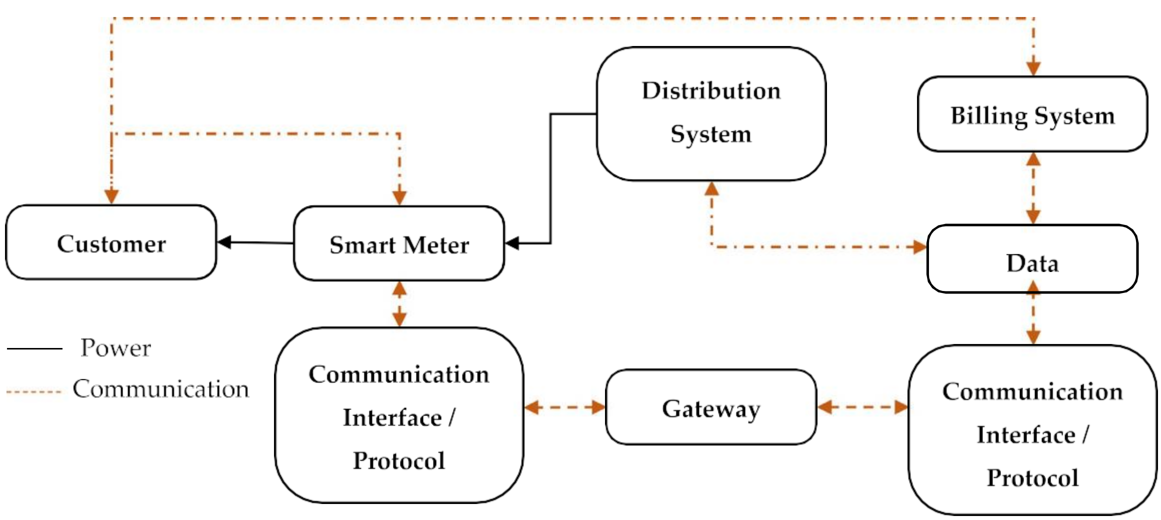

Figure 9. Block diagram of Smart Energy Meters.

hicle charging, operating washing machines, etc. can be automatically scheduled to operate in the off-peak hours.

(c) Smart Energy Meters

The development of smart meters is the advancement of the previ- ously in use electromechanical energy meters and its working mecha- nism is presented in Figure 9. The electromechanical meters operate ac-cording to the number of revolutions of an electrically conductive metal-lic disc rotating with proportional to the power consumed [108], while advanced metering infrastructure or smart meters enables two-way com- munication between supplier and consumer to ensure the reliable power supply by minimizing the outage and losses, they can optimize the en- ergy costs along with remote monitoring and control facility [109].

Smart energy meters are used to record energy consumption hourly or more frequently and reported at least daily to the utility service provider [110,111]. Smart metering infrastructure also plays a vital role in other applications like detection of electricity theft, improved system security, load dispatch and control along with development of smarturban cities [110,112].

(d) Distribution system automation

The electric power distribution system is an important part of elec- trical power systems in the delivery of electricity to consumers. For the flexible control of distribution systems, distribution system automation (DSA) has played a vital role which can enhance efficiency, reliability, and quality of electric supply. Figure 10 shows the basic architecture of DSA. Distribution Automation Systems have been defined by the Insti- tute of Electrical and Electronics Engineers (IEEE) as systems that en- able an electric utility to monitor, coordinate, and operate distribution components in a real-time mode from remote locations [113]. For mak- ing distribution automation more intelligent, efficient and cost-effectiveworldwide research and development are focused on the areas of rev- olution of communication technologies and application of IEC 61850 protocol in the distribution automation [114]. Until these days, DSA

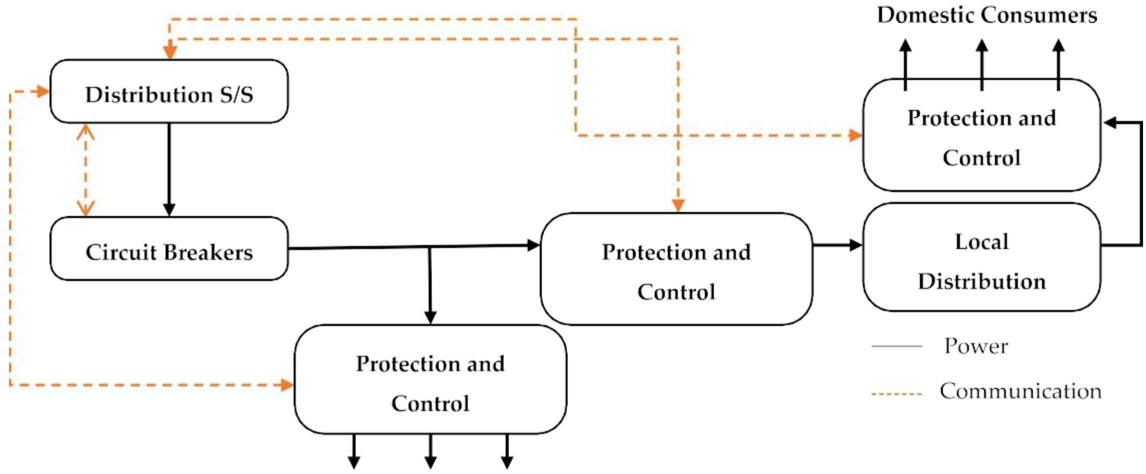

Figure 10. Working principle of Distribution System Automation.

technology is established not just as remote operation and control of substation and feeders, but it is transforming into a self-healing power system that responds immediately to real-time appropriate actions, in- telligent load forecasting, and demand side management.

Different electricity authorities have also put forward the plan to prepare Geographic Information System (GIS)-based inventory to track its poles, transformers, cables, consumers' connections to each trans- former to know all the data & their existences in the distribution sys- tem as a pathway to the development of DSA. This system would also help the system engineers to get actual data of poles, transformers, and consumers' capacity and also to balance the transformer's load as per connection to the consumer [103, 115]. The additional benefits of this system would be a quick assessment of fault detection and localization which supports the No-light/Customer Care section to troubleshoot thefaults in a quick and easier way.

4. Standardizations related to Smart Manufacturing Technology

Smart manufacturing technology is the collaborative output of in- formation technology, industrial manufacturing technology and human creativity leading into a rapid revolution of manufacturing system. "Cur- rent Standards landscape for Smart Manufacturing Systems" publishedby National Institute of Standards and Technology (NIST) in February 2016 [20], "German Standardization Roadmap Industry 4.0" published by German Commission for Electrical, Electronic & Information Tech- nologies of DIN and VDE in 2015 [116], "National Smart Manufacturing Standards Architecture Construction Guidance" published by Ministry of Industry and Information technology of China (MIIT) and Standardiza- tion Administration of China (SAC) in 2015 [117] are the leading stan- dardizations published for the implementation of smart manufacturing system in the various parts of the globe.

Besides these, International Electrotechnical Commission (IEC), In- ternational Society of Automation (ISA), International Standards Orga- nization (ISO), American National Standards Institute (ANSI) has also published the standardization in different aspects of smart manufactur- ing system. The various published standardizations and their major role in smart manufacturing system has been tabulated in **Table 7**.

5. Characteristics and Challenges of Smart Manufacturing Systems

The smart manufacturing systems are capable to cope up with var- ious challenges and complexities faced by the existing industries, but there still exists some of the challenges during the implementation of smart manufacturing systems. Based on various dependent variables, smart manufacturing systems are considered to be faced by security is- sues, lack of system integration, lack of return of investment in new technology and financial issues during the erection of new smart manu- facturing systems and/or during the upgrade of existing industries with smart manufacturing technology. The challenges faced by the smart manufacturing systems and their possible solutions are described below.

5.1. Security Issues in Smart Manufacturing

The smart manufacturing system means the use of an integrated net- work system in a manufacturing system for sharing information between manufacturing or machining units to the end customers. For this pur- pose, it requires network connectivity and is arranged especially through the internet. Sharing information through the internet requires security of data and information throughout the system in various points with global unique identification and end to end data encryption [122]. And hence, every node of the network should be protected against external attacks and data misuse. The thing that is most importantly considered while designing the networked systems such as smart manufacturing systems is to ensure the security of the system and the overall process.

5.2. System Integration

Another challenge of the implementation of a smart manufacturing system is the integration of new technology equipment with the exist- ing ones [61]. The compatibility of existing devices to the new devices causes various problems in the implementation of smart manufactur- ing technologies. The old machinery which is being controlled by some communication protocols might be outdated and new devices may have a different protocol. Also, the machine to machine communication and the interconnectivity of the system requires the better communication system. The recent manufacturing systems require IPv6 connectivity tosupport more devices connected at the same time.

5.3. Interoperability

The interoperability is the ability of different systems to understand and access each other's functions independently [123]. This feature sup- ports the data and information exchange between them independent ofthe manufacturer of their hardware or software. There are four levels of interoperability of I4.0, namely operational, systematical, technical and semantic. The operational interoperability correlates CPS with I4.0 and concerns with the conceptual structure of I4.0. Systematical interop- erability concerns with standards, guidelines, principle methodologies and models. The technical interoperability distinctly establishes tools

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Table 7
List of Standards related to SMS [118-121].

Published Standard	Major Role
IEC 61131	Standards set for programmable logic controllers, defines the hardware and software requirements, programming languages and fuzzy logic control, functional safety, a communication interface for industrial system
IEC 61850	Defines communication protocols for intelligent electronic devices at electrical substationsIEC
62443 (ISA99)	Gives the guideline for implementation of secured industrial automation systems
IEC 62541	Cross-platform Machine to machine communication protocol with service-oriented architecture for industrial automation focusing on secured communication of industrial equipment.
IEC 62591	Wireless sensor networking technology for industrial automation based on Highway Addressable Remote Transducer Protocol (HART)
IEC/PAS 62030	Designed to support the requirements of data distribution systems in industrial automation systems
ISO 15704	Industrial automation systems — Requirements for enterprise-reference architectures and methodologies
ISO 19439	Standard for enterprise modelling and enterprise integration
ISO 19440	Computer integration of the information aspects of manufacturing, including the management and control technology and the required human tasks
ISO 20140	Concerns with the environmental influence of manufacturing processes
ISO 50001	Concerns with energy management in the industries.
ISO 9000	This addresses the standard for consistent quality assurance of the products
PackML (Packing Machines Language)	Industrial automation standard for packaging machines
ISO 15926	The standard for data integration, sharing, exchange, and hand-over between computer systems.
IEC 62890	Life-cycle management for systems and products used in industrial-process measurement, control, and automation
IEC 62453	Used for integrating the HART technology into the Field Device Tool standard
SysML (Systems Modeling Language)	General-purpose modeling language supporting specification, analysis, design, verification and validation of system-of-systems
IEC 61499	Standardization of function blocks for industrial process measurement and control systems
IEC 61804	Function blocks for process control and electronic device description language
IEC 61508	Functional Safety of Electrical, Electronic, Programmable Electronic safety-related Systems
IEC 61511	Ensuring the safety of industrial process through the deployment of instrumentation tools
ISO 13849	Applicable for the safety of machinery control systems related parts
IEC 62714	Engineering data exchange format for use in industrial automation systems engineering
ISO 18828	Describes the production planning along with production order management, early-stage product design, inventory management, resource visualization and process simulation
ISO/IEC 27001	Specifies a management system intended to bring information security under explicit management control
EN 50170	General purpose field communication system
IEC 61158	Digital data communications for measurement and control - Field bus for use in industrial control systems
ANSI/ISA-88.01	Batch Control
ANSI/ISA-95.00.01	Enterprise-Control System Integration
ISO/DIS 15745-1	Industrial automation systems and integration – Open systems application integration frameworks

and platforms for technical and ICT environment and related software. Semantic interoperability deals with information exchange among dif- ferent levels of institutions and people [50].

Without proper matching of the communication protocols and stan-dards, the feature of interoperability may not be achieved efficiently. The dissimilarities between the communication bandwidth, operational frequency, mode of communication, hardware capabilities etc. deter- mine the limitations of interoperability of the system.

5.4. *Safety in Human-Robot Collaboration*

A cobot or lightweight robot is a particular type of robot which can safely and physically interact with humans in the workspace and can work together by introducing new paradigms from Human-Machine in- teraction(HMI) [124,125]. The international federation of Robotics de- fines Human-Robot collaboration as the ability of the robot to coordinate with the workers in the industrial environment to perform the special- ized tasks [126]. The main considerations should be done with occupa- tional health and safety of personnel working in the site, any hazardous environment should be avoided and necessary occupational health and safety should be maintained. The main attention should be given while implementing the CPS system or industrial robotic systems to minimize any types of mechanical, electrical, thermal, noise, vibration, radiation, material/substance, work environment caused any hazards in the work-place in an industry [124].

5.5. *Multilingualism*

The smart manufacturing systems should be handling multilingual operations which should be able to interpret any instructions given in human language into the machine language to instruct the machine for the desired operation [127]. To make the term smart manufacturing to be realistic and implement AI and advanced technologies in manufac- turing system, it should be able to get the instructions directly from theoperator either in voice or in text format.

5.6. *Return of Investment in New Technology*

While shifting into another advanced technology in an existing man- ufacturing system, the financial analysis and return of investment are analyzed very carefully [61]. The additional investment that should be made to adopt newer technology would be compared with the losses in production during an upgrade and the time acquired to recover the re- turn of investment with the income with existing system influences the adaption of newer technology.

6. Opportunities and Future Directions of Smart Manufacturing in the Global Market

Referring to the various research outcomes and the reports of differ- ent organizations, the smart manufacturing system has a huge market opportunity and is being widely adopted in the manufacturing system throughout the world. Zhengxin et al. [128], illustrated the small and medium enterprises are prone to adopt intelligent manufacturing. Ac- cording to McKinsey & Company report presented by Manyika [22], the accommodation and food services have a tendency to automate by 73%, manufacturing, transportation, and warehousing industries have the potential of 60% to automate. Since these sectors have the highest possibility for automation, they are now being the center of study for

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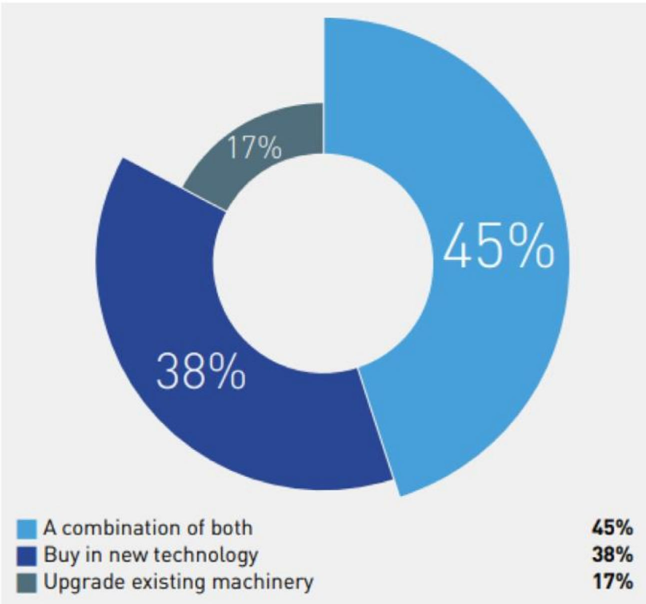

Figure 11. WBR Digital's survey report on adapting smart manufacturing [61].

implementing the latest technology for improving productivity better performance.

The WBR survey report in 2017 [61] concluded that their survey participants are eager to upgrade with the new manufacturing system very soon, out of them 38% were found to be planning to install new technology, 45% were found to upgrade their existing machinery with smart manufacturing system and 17% of them were planning for com- bination of these both (illustrated in Figure 11). Qin et. al. [129], an- alyzed the gap between existing manufacturing with the future man- ufacturing system and shows the necessity and opportunities of smart manufacturing/industry 4.0 technology in a manufacturing system. As shown in Figure 12, the current manufacturing systems lack many com-ponents and functions compared with the smart manufacturing tech- nologies. The major considerations of smart manufacturing systems like self-configuration, self-optimization, early awareness, decision making and predictive maintenance are still lacking in the most advanced man- ufacturing system i.e in reconfigurable manufacturing systems too.

The complexity of the system, the interaction of machines and their inter-relation, roles of each subsystem, along with their working mech- anism and interdependencies defines the architecture of the industrial automation system [130]. The automation technology has exposed the scope of sharing the information and data across the connected system, and the process handling and interoperability between the machines has been increased rapidly facilitating easiness in flexible resource and process management, proper exception handling [131].

The use of automated and intelligent systems has enabled the op- portunity to next level of manufacturing commonly termed as smart manufacturing or intelligent manufacturing which utilizes the data and information from the end-users through cloud computing and fastens the customized product manufacturing [132, 133]. The use of an au- tomated and robust system is the requirement to meet today's demand in the market. This technology has also optimized the production costs, increased verities of design and fastens product delivery time.

7. Discussion and Conclusion

The smart manufacturing systems have been playing a vital role in the implementation of better manufacturing technology in the current industrial age. The smart manufacturing technology improves the oper-ational efficiency, productivity and has great impact in the global econ- omy. It has been found that emergence of IoT and IIoT has been play- ing a vital role in uplifting the manufacturing system equipped with smart manufacturing systems. Various researches in manufacturing sys- tem have investigated that there are many industries which are intend- ing to upgrade their industries with smart manufacturing systems. The challenging factor for a smart manufacturing system is being the issues with compatibility of their existing machines and systems with the new technology.

Smart devices like IoT and CPS has now emerged as a universal paradigm that can drastically transform any industries equipped with sensing, identification, remote control and automated control capabili- ties. The industry 4.0, Society 5.0, Made in China 2025 and Industrial Internet all has the technological base of Internet and the interconnected devices, which basically has the theme of process control through less human interventions and smart decisions which has a very huge impact on the global market. This paper explained about the smart manufactur- ing system and its associated technologies, newly introduced paradigms, associated technologies and their impact in smart manufacturing tech- nology, related standardizations and the challenges and opportunities of smart manufacturing system has been discussed.

As seen through various Internet integrated systems, the inter-link between the physical objects through the internet or the IoT has ex- plicitly played a vital role in the upgrade or upliftment of the existing systems and procedures. Internet technology has seen to be enhancing

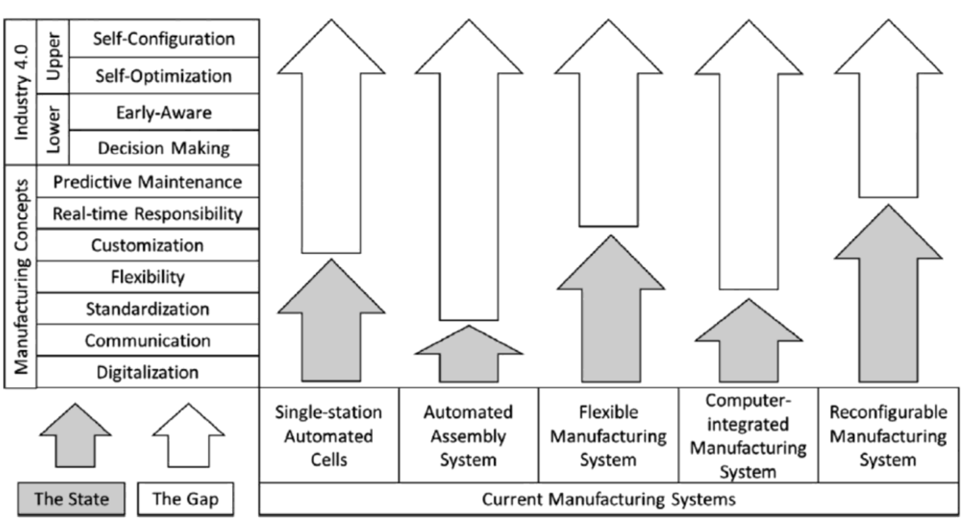

Figure 12. Technological Gap Between Cur- rent Manufacturing System and Industry 4.0 [129].

the SCADA systems in the automation sector by introducing the remote sensing and control facilities. Due to the interlinkage of physical ob- jects like public transportation, power grid operations and monitoring, better health care by tracking the body vitals and frequently reporting, coordination of live traffic, tracking of assets, interconnected fleet man- agement, self-driving vehicles like AGVs through internet has improved the lifestyle as well as the socio-economic status of the people around the world. The use of IoT in different sectors has helped to reduce the people to work in hazardous environment by using the automated sys- tems and increased productivity too.

For the successful implementation of smart manufacturing technol- ogy, the associated technologies like artificial intelligence, cyber phys- ical systems, big data processing, augmented and virtual reality, IoT, robotics technology etc. needs to be developed properly in the industrial area. The defined functions of these technology have not been found to be in common in the current manufacturing scenario and lacks a big gap from the conceptual smart manufacturing system and the existing manufacturing system. Also, for the proper communications between the machines in the industries, there should be implemented the latest IPv6 technology which supports more devices in interconnection.

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