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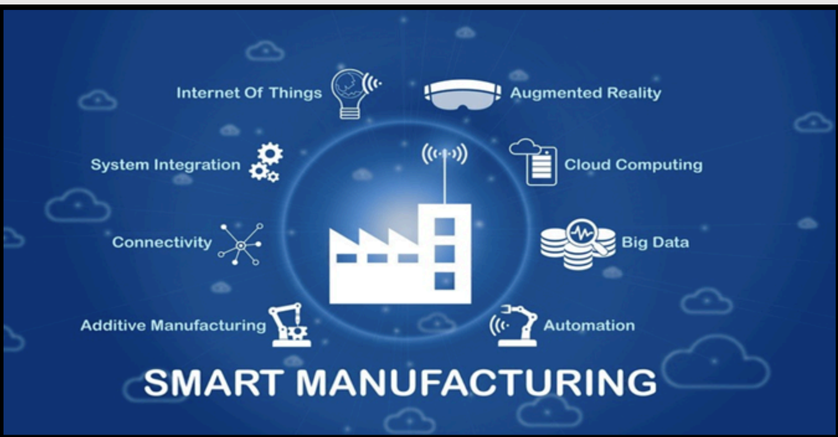
TECHNICAL REPORT

Industry 4.0: The Future of Smart Manufacturing

TEC 31238:2025

Working Group: Industry 4.0 / Smart Manufacturing



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DEPARTMENT OF TELECOMMUNICATIONS
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Foreword

As the technical arm of Department of Telecommunications (DoT), National standardization body for telecommunications in India and National enquiry point for WTO-TBT in the telecom sector, the Telecommunication Engineering Centre (TEC) plays a pivotal role in shaping India's digital transformation through development of national standards and alignment with global best practices.

TEC has been actively engaged with international standardization bodies such as ITU, oneM2M, 3GPP, ETSI, APT, IEEE, etc and has successfully adopted oneM2M Release 2 and 3 specifications as National Standards. Complementing these efforts, TEC has released twenty three technical reports in the IoT/M2M domain, covering key verticals like Smart Cities, Transport, Agriculture, Power and Health as well as critical horizontal layers such as M2M Architecture, communication technologies and security. The insights from these reports directly contribute to policy formulation and standardization, fostering an inclusive and robust IoT ecosystem in the country.

TEC is the nodal authority for Mandatory Testing and Certification of Telecommunication Equipment (MTCTE) and ensures testing as per the Essential Requirements (ERs) formulated for various telecom products viz, IoT Gateway, Smart Electricity meter, Tracking device etc.

This Technical Report on 'Industry 4.0 – The Future of Smart Manufacturing' is a part of TEC's ongoing efforts to provide forward-looking guidance for emerging technologies in telecommunications and related ICT sectors. The report is a result of extensive stakeholder consultation in the Working Group, drawing on the collective expertise of industry, academia and government. It offers a comprehensive view of how advanced communication technologies such as 5G, AI, IIoT, Edge Computing and Cyber-Physical Systems can enable India's industrial sector in transitioning towards more sustainable and smart manufacturing practices. This Technical Report also lists down the challenges in adopting Industry 4.0, particularly by MSMEs/SMEs, for conversion from traditional factories to smart factories and discusses the importance of standardization and digital adoption in overcoming those

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challenges, highlighting the role of various stakeholders including government to support this technological transformation.

This Technical Report reflects role of TEC, as a standardization body and a proactive enabler of digital transformation. I extend my appreciation to IoT division and all the members of the Working Group, whose insights and domain expertise have enriched the quality of this Technical Report. I am confident that this document will prove valuable in shaping informed policy decisions, driving industry-led innovation and fostering collaborative action towards India's smart manufacturing future.

(Tripti Saxena)

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Executive Summary

Industry 4.0 represents a paradigm shift in industrial production, driven by the convergence of advanced digital technologies that enable the creation of intelligent, interconnected systems. At its core, this revolution is powered by cyber-physical systems (CPS), the Internet of Things (IoT), artificial intelligence (AI) and machine learning (ML), big data analytics, digital twins, cloud computing, autonomous robotics, simulation, and additive manufacturing. These technologies facilitate seamless machine-to-machine (M2M) communication, enabling factories to operate with enhanced efficiency, adaptability, and intelligence. Automation and robotics play a central role, with AI functioning as the cognitive engine that empowers smart factories to enhance productivity and foster collaborative interactions between human operators and intelligent machines.

The Fourth Industrial Revolution builds upon previous industrial advancements, from mechanization and steam engines to electronics and automation. Industry 4.0 introduces smart, self-optimizing systems that enhance productivity and efficiency, enabling mass customization. The impact of Industry 4.0 spans all sectors and will bring about significant changes to the global economy, including new labour dynamics, rise of in-shoring and shifts in outsourcing practices. Industry 4.0 is driving a growing demand for skilled labour, particularly in STEM (Science, Technology, Engineering and Mathematics) fields, creating new opportunities for high-quality employment and enabling the workforce to engage in more innovative and value-added roles.

The transformation driven by Industry 4.0 will lead to more dynamic, efficient and sustainable production systems, fostering energy-efficient practices and reducing material consumption. It will support the circular economy through the reuse and recycling of products and encourage new product designs using advanced materials. Additionally, Industry 4.0 will change the nature of work, requiring new technical and interpersonal skills and promoting remote, flexible and on-demand work. This will reshape job markets and production processes globally, presenting both opportunities and challenges.

Industry 4.0 presents a transformative opportunity for global industries, but its successful implementation requires thoughtful planning and collaboration. Enhancing infrastructure and following international frameworks can help fully harness the potential of emerging technologies. Promoting standardization and interoperability will enable seamless integration of diverse systems, while robust approaches to data governance can ensure security, transparency and trust. Strengthening intellectual property frameworks and fostering supportive policies can further stimulate innovation with responsible application of new technologies. Ensuring the reliability and stability of cyber-physical systems (CPSs), alongside a focus on ethical considerations, privacy and inclusive growth, will help create an environment where businesses of all sizes can thrive and contribute to a more connected, resilient and equitable industrial future.

Despite these challenges, Industry 4.0 offers numerous opportunities that can drive economic growth and innovation. It can lead to economic gains through increased revenues, driven by lower transaction and transportation costs. Productivity and output can become more reliable and consistent, resulting in higher-quality products. A shift towards mass customization, particularly for small and medium-sized enterprises (SMEs), will open new markets. Industry 4.0 also enables broader innovation across multiple sectors, significantly impacting economic growth. Additionally,

it promotes energy-efficient, environmentally sustainable production systems, effective use of resources and enhanced food security and safety. The health and safety of workers can be improved, while new systems for education and training will better equip the workforce. The evolving nature of work will lead to more remote, flexible, and on-demand jobs, reshaping traditional organizational structures.

This Technical Report examines the technologies powering Industry 4.0 and its associated aspects. It delves into the historical background of Industry 4.0, highlighting its evolution and significance. Key technologies driving this revolution, such as automation, IoT, AI/ ML and 5G are explored in depth, along with their impact on supply chain optimization and advancements in quality control. The report also emphasizes the growing importance of human-robot collaboration, as well as the role of customization and flexible manufacturing in meeting market demands. Additionally, it lists down the challenges in adopting Industry 4.0, particularly by MSMEs/SMEs, for conversion from traditional factories to smart factories and discusses the importance of standardization and digital adoption in overcoming those challenges, highlighting the role of various stakeholders including government to support this technological transformation. Various use cases have been compiled and described in this report to illustrate the transformative effects of Industry 4.0, demonstrating how manufacturers can achieve unprecedented levels of efficiency, agility and innovation by embracing these advancements.

The Working Group on 'Industry 4.0/Smart Manufacturing' was constituted comprising of diverse range of stakeholders including industry experts, academic institutions, startups and related members, with the following Terms of Reference (ToR):

1. To consult with stakeholders to envisage requirements of telecom/ ICT/ loT in Industry 4.0/ Smart manufacturing.
2. To study national and international best practices, benchmarks, policies/ standards being adopted for Industry 4.0/ Smart manufacturing.
3. To compile use cases/ case studies in Industry 4.0/ Smart manufacturing.
4. Typical challenges faced in implementation of Industry 4.0 and success stories
   4.1 Conventional factories conversion to smart factories.
5. Compilation of libraries (repositories) of various components e.g. MTConnect, OPC-UA, oneM2M.
6. To recommend loT/ ICT based standards/ specifications/ guidelines to facilitate the growth of Industry 4.0/ Smart manufacturing ecosystem in India.

1. Introduction

Industry 4.0, also known as the Fourth Industrial Revolution, represents a fundamental change in the way industries operate, driven by the integration of digital technologies. This new era is characterized by the convergence of cyber-physical systems, Internet of Things (IoT), artificial intelligence (AI) and advanced data analytics. These technologies enable smarter, more efficient and interconnected industrial processes.

The word 'Industry 4.0' was coined in 2011 by the German project, led in collaboration with universities and business enterprises by the Federal government. In particular, the development of sophisticated production techniques to increase productivity and efficiency of domestic industries was a strategic initiative. An innovative and convergent set of technologies that add value across the product life cycle has resulted in a new phase of industrial production[1]. The socio-technological growth of the human function in production systems is a key component of the new industrial phase, in which all activities along the value chain are conducted using intelligent techniques (smart factories)[2].

Industry 4.0 marks a major shift in industrial production by integrating advanced technologies like cyber-physical systems (CPSs), Internet of Things (IoT), big data, cloud & edge computing, autonomous robots and additive manufacturing. These systems enable machines to communicate and perform autonomous tasks, enhancing collaboration between humans and robots in smart factories for mass customization.

Unlike previous industrial revolutions, which focused on mechanization, electricity and automation, Industry 4.0 introduces smart, self-optimizing systems that can self-cognize and self-customize. This evolution will transform global industries, potentially reducing outsourcing through technologies like 3D printing, while increasing demand for high- and low-wage jobs, potentially polarizing the labour market.

Industry 4.0 will also drive sustainability by optimizing material and energy use, promoting circular economies and reducing waste.

The transformation will require new skills, particularly in STEM fields, and reshape the nature of work with more remote, flexible and on-demand opportunities. Enabling technology and education across developed and developing nations may accelerate the Industry 4.0 transformation in a faster and efficient manner

Industry 4.0 is often used interchangeably with the term 'smart manufacturing', as both refer to the integration of advanced technologies like automation, IoT and AI to create more efficient, flexible, and autonomous production systems. The key pillars of Industry 4.0 are summarized in figure 1 below:

[1] H. Takeyama, N. Iijima, Machin ability of glass fiber reinforced plastics and application of ultrasonic machining, CIRP Annals 37 (1) (1988) 93–96.
[2] K.S. Kim, D.G. Lee, Y.K. Kwak, S. Namgung, Machin ability of carbon fiber-epoxy composite materials in turning, J. Mater. Process. Technol. 32 (3) (1992) 553–570.

Figure 1: Typical 8 Pillars of Industry 4.0

The intelligent manufacturing concept, the foundation of Industry 4.0, describes a system which is adaptable to various kinds of changing conditions and products. Flexible lines adapt production processes automatically to meet different product types and changing conditions[3]. This provides increased quality, efficiency and flexibility, as well as large-scale and sustainable production of customized products, thanks to reduced consumption of resources.

After seeing constant progress on the back of mechanization, electrification and the advent of the assembly line over two centuries, the global manufacturing industry adopted information technology in the 1960s, when computers came into the forefront of development, simplifying human effort. From then to now, both operational technology and information technology have come a long way, unleashing a vast plethora of possibilities on the factory floor through Industry 4.0. This journey of transformation from mechanization to digitization can be effectively visualized through figure 2 below, that traces the evolution of Industry 4.0 across its key industrial revolutions.

[3] C.W. Wern, M. Ramulu, A. Shukla, Investigation of stresses in he orthogonal cutting of fiber-reinforced plastics, Exp. Mech. 36 (1) (1996) 33–41.

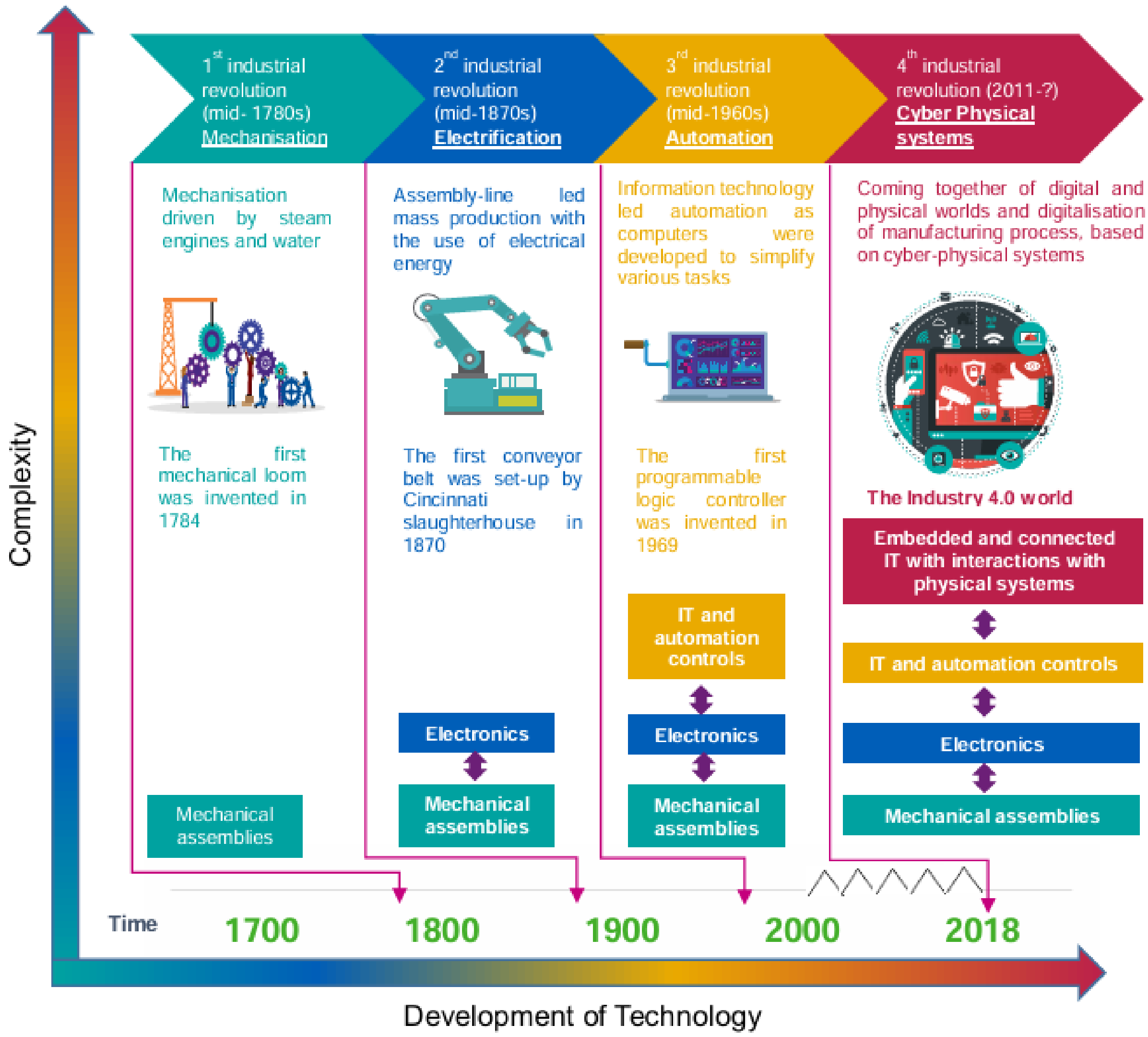

Figure 2: Evolution of Industry 4.0

[Source: KPMG][4]

The transformational nature of the fourth Industrial Revolution particularly lies in its ability to digitally integrate isolated systems using various synergistic technology levers, unleashing unprecedented levels of value.

While Industry 4.0 is powered by advanced technologies like IIoT, AI and cloud computing, its successful adoption depends far more on people and top management.

Following are key requirements for Industry 4.0 to be successful:

i. **Top-Down Approach**: The top management has to be committed to the goals (both short term and long term). The need and advantages have been "marketed" internally to cross-functional teams, operations and down to the floor operator.

ii. **Managing Resistance to Change**: As the operation team remains occupied with daily challenges, any new system is seen as a burden. Also, there is fear of "AI taking jobs" and

[4] https://resources.aima.in/presentations/AIMA-KPMG-industry-4-0-report.pdf

lack of digital skills. These aspects must be handled throughout the project by involvement and training of stakeholders.

iii. **Start with KPIs that matter most**: There are various technologies available for Industry 4.0, often marketed through fancy dashboards and AI tools. It is of utmost importance to review the existing manufacturing process and identify critical operations and pain points. Accordingly, target KPIs for measurement and improvement to be identified. As it is said, “if you can measure it, you can improve”. Finally, time and money should be invested in Industry 4.0 projects on the target processes should initiated with phase-wise goals.

iv. **Actionable Industry 4.0 – One Phase at a Time**: It is imperative to understand that Industry 4.0 is not a one day (or one-month journey) which is implemented by a supplier. Phase wise targets, its implementation and actionable output must be carefully monitored.

1.1 Machine-to-Machine (M2M) communication

Machine-to-Machine (M2M) communication refers to the automated exchange of data between devices or machines without the need for human intervention. This technology allows devices to share information and execute actions based on the data exchanged. In industrial contexts, M2M communication involves sensors and meters transmitting data (such as temperature, inventory levels, etc.) through various networks (wireless, wired, or hybrid) to application software, which then processes and interprets this data into actionable insights.

In the era of Industry 4.0, M2M communication has become a cornerstone of smart manufacturing and industrial automation. The advanced connectivity and interoperability of devices enable a seamless flow of information across different levels of the production process. Here's how M2M communication enhances Industry 4.0:

- Real-Time Data Exchange
- Predictive Maintenance
- Improved Efficiency and Productivity
- Supply Chain Integration
- Quality Control
- Energy Management

M2M communication is a critical enabler of Industry 4.0, providing the foundation for advanced automation, real-time data analytics, and seamless integration across industrial processes. By leveraging M2M technologies, industries can achieve higher efficiency, productivity, and innovation, paving the way for the future of smart manufacturing.

1.2 Internet of Things (IoT)

The Internet of Things (IoT) is defined as the network of physical objects or things, embedded with sensors, software and other technologies that connect and exchange data with various devices and systems over the internet or other communication networks. The primary goal of the Internet of Things is to enhance efficiency, automate processes and enable new applications and services by connecting the physical world to the digital world. An IoT system collects data from sensors installed in IoT devices and transfers that data through an IoT gateway for it to be analyzed by an application or back-end system to take informed decisions.

International Telecommunication Union (ITU) has defined IoT as "A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" [ITU-T Y.2060 (06/2012)]. Figure 3 below shows the architecture of an IoT ecosystem.

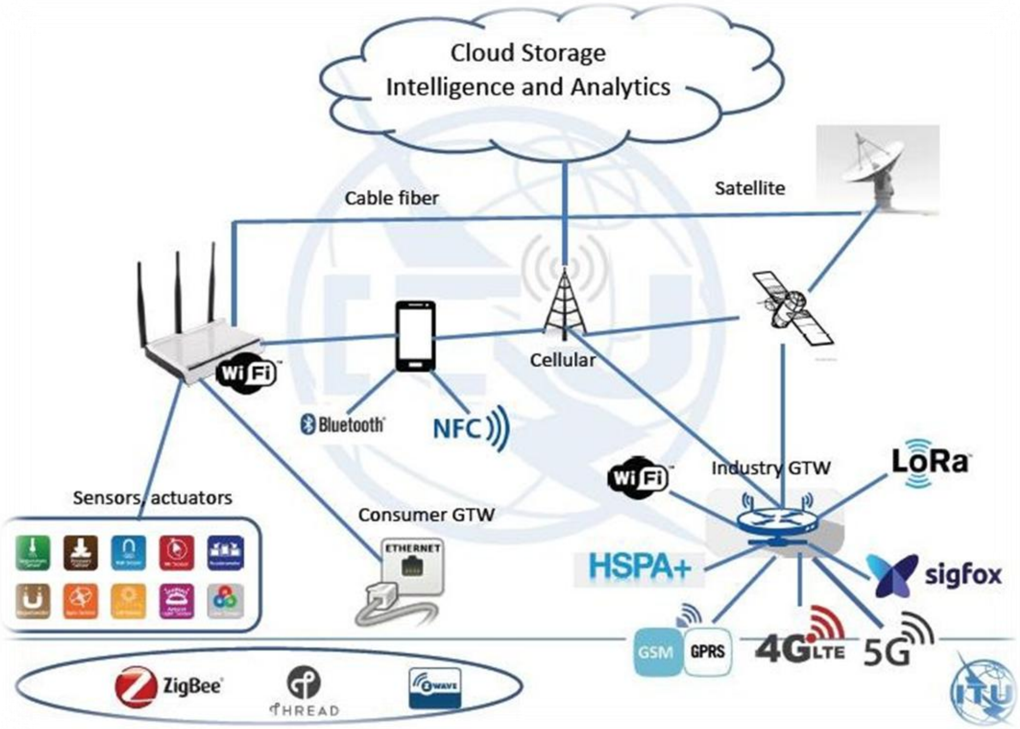

Figure 3: IoT Architecture

[Source: Adapted from ITU]

IoT gets benefitted by several other technologies such as Machine-to-Machine (M2M) communication, Artificial Intelligence (AI), Machine Learning (ML), Big Data, Cloud/Edge Computing, Cellular & Non-cellular communication technologies. Research and development in these technologies will further help in creating smart infrastructure in various verticals and in turn improving the quality of life of citizens. Applications of IoT in various verticals are depicted in figure 4 below:

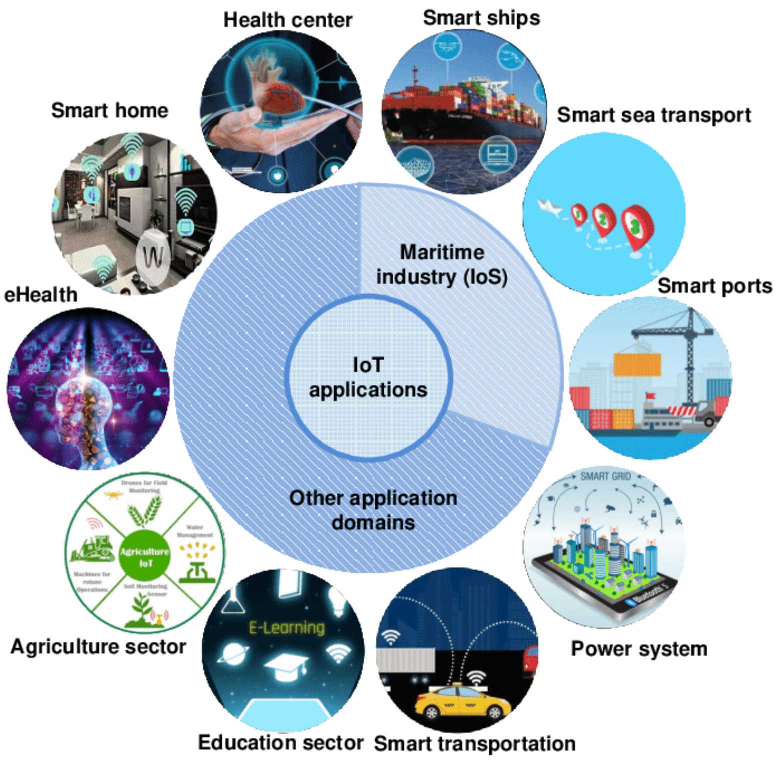

Figure 4: IoT Applications

[Source: Research Gate][5]

1.3 Smart Manufacturing: Functional layering perspective

As per ITU Recommendation ITU-T Y.4003[6] smart manufacturing is defined as "A generic term for advanced processes, systems, methods and organizations throughout the manufacturing ecosystem based on advanced computing and manufacturing technologies, as well as existing and evolving interoperable information and communication technologies, aiming to integrate this ecosystem, innovate the development of products and services and improve the efficiency and reliability of manufacturing's life-cycle management, together with increasing performance, safety and environmental sustainability.

NOTE – The concept of smart manufacturing encompasses all aspects of the manufacturing activities, from design, sales, production, logistics and service.

Smart manufacturing has the potential to fundamentally change how products are designed, manufactured, supplied, used, re-manufactured and eventually retired. As shown in figure 5, smart manufacturing can be represented from the functional layering perspective via three layers, respectively, application layer, integration layer and life-cycle management layer.

[5]https://www.researchgate.net/publication/341160084_Internet_of_Ships_A_Survey_on_Architectures_Emerging_Applications_and_Challenges
[6] https://www.itu.int/ITU-T/recommendations/rec.aspx?id=13634

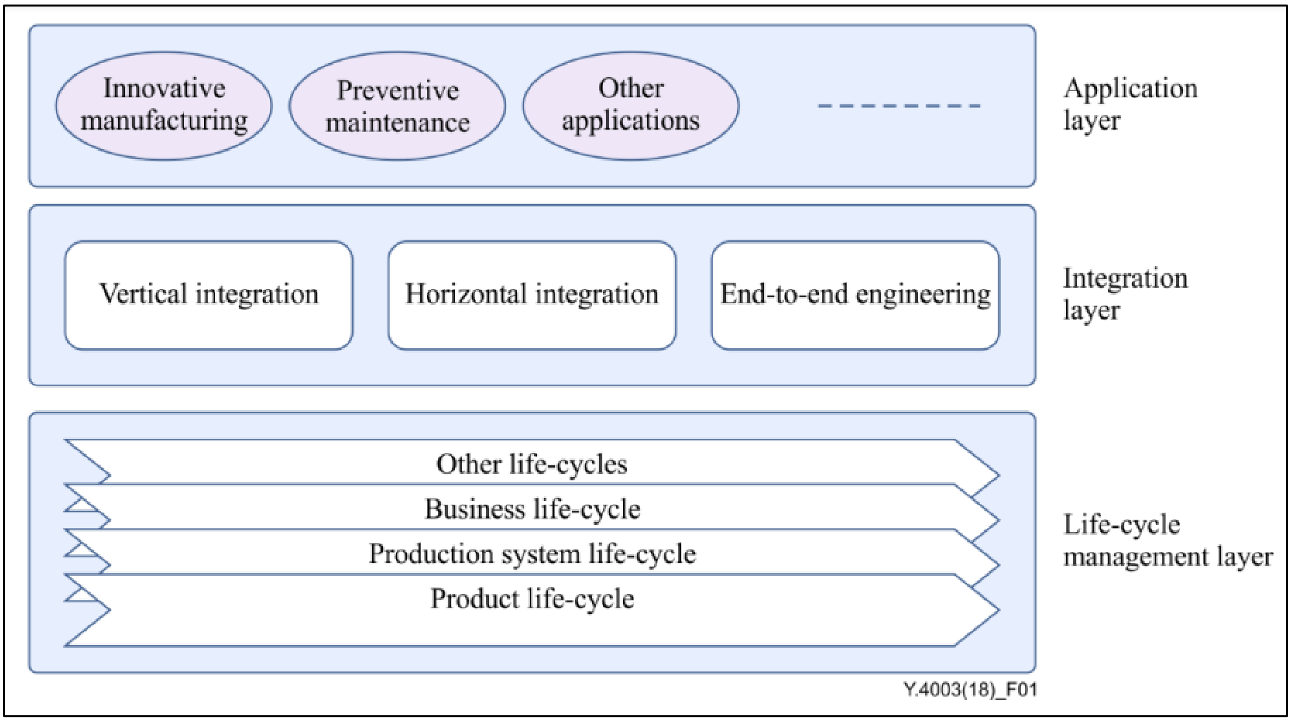

Figure 5: Overview of smart manufacturing from the functional layering perspective

[Source: ITU-T Y.4003]

The life-cycle management layer encompasses a broad scope of systems in the manufacturing business, including those for production, management, design and engineering support.

In terms of smart manufacturing process phases and involved stakeholders, this layer addresses product life-cycle, production system life-cycle and business life-cycle. Other life-cycles, with respect to specific manufacturing business scenarios, may be addressed too.

The product life-cycle concerns the product development, the engineering of the corresponding production system, the manufacturing of the product by the production system, the use of the manufactured product by the user, and the product's recycling and/or dismantling. The product lifecycle deals with the information flows and controls from the early product design phase until the product end-of-life. All information generated over the life-cycle is linked through the entire process. The production system life-cycle focuses on design, deployment, operation and decommissioning of an entire production facility.

The business life-cycle addresses the functions related to the supplier-customer interactions.

The integration layer enables the integration of all the resources, systems and processes involved in different life-cycles associated with the value chain of the product, through the whole manufacturing system levels, for the establishment of an environment for the smart manufacturing applications. As illustrated in Figure 5, it addresses vertical integration, horizontal integration and end-to-end engineering.

Vertical integration refers to the integration into a production system of the various manufacturing elements at the different levels of the manufacturing system (system hierarchy) e.g., from sensors and machines to control systems, production management systems and corporate planning systems.

Horizontal integration refers to the integration of the various manufacturing elements for the support of and/or execution in, the different phases of the manufacturing processes, involving exchange of materials, energy and information both within an enterprise (e.g., inbound logistics, production, outbound logistics, marketing) and between different enterprises (value networks), up to and including an end-to-end solution.

The end-to-end engineering refers to the integration of the engineering process in order to connect each phase of the product life-cycle across the product's entire value chain and across different enterprises. End-to-end engineering enables the integration of the cyber and physical spaces involved in the manufacturing process on the basis of digitization.

The application layer addresses applications of smart manufacturing, aiming to satisfy different purposes. The applications are enabled by the integration layer capabilities.

1.4 Industrial Internet of Things (IIoT)

As per Recommendation ITU-T Y.4003[7], Industrial IoT is “An Internet of things based enabling approach for industrial transformation, by taking advantage of existing and emerging information and communication technologies.”

NOTE 1 – Emerging information and communication technologies include technologies for smart machines, robots, advanced industrial networks, industrial cloud computing and industrial data processing.

NOTE 2 – The industrial transformation enabled by the industrial Internet of things empowers the industry with, but not limited to, improved efficiency, intelligent production, reduced energy consumption, advanced collaboration modes and new business models. Industrial Internet of things enables smart manufacturing providing enhanced capabilities in support of manufacturing.

Currently, only a fraction of a manufacturer’s sensors and machines are networked and utilize embedded computing. These systems are typically organized in a vertical automation pyramid, where sensors and field devices with limited intelligence feed data into automation controllers, which then relay information to a central manufacturing-process control system. However, the advent of the Industrial Internet of Things (IIoT) is poised to transform this setup. More devices—including unfinished products—will be equipped with embedded computing and connected using standard technologies. This connectivity allows field devices to communicate and interact with each other and with centralized controllers as needed, decentralizing analytics and decision-making and enabling real-time responses.

The integration of IIoT can lead to significant cost savings. By optimizing resource use and reducing downtime through predictive maintenance and real-time monitoring, manufacturers can lower operational costs and enhance profitability. Additionally, the data generated by interconnected

[7] https://www.itu.int/ITU-T/recommendations/rec.aspx?id=13634

devices provides valuable insights for continuous improvement, driving innovation and operational excellence.

Industrial Internet of things (IIoT) infrastructure

Smart manufacturing provides an advanced production mode based on the deep integration of advanced manufacturing technology and new generation information technology, which runs through the whole product life cycle such as design, production, sales, logistics and services. Smart manufacturing has the characteristics of self-perception, self-decision-making, self-performing, self-adaptation and self-learning, and it aims to improve the quality, efficiency and flexibility of the manufacturing industry.

IIoT infrastructure plays a crucial role in smart manufacturing, and provides supporting smart manufacturing capabilities, as presented in [ITU-T Y.4003]. This clause introduces technical aspects with regard to the IIoT Infrastructure utilized for smart manufacturing.

Figure 6 depicts a conceptual framework of the IIoT infrastructure from the Internet of things (IoT) and smart manufacturing points of view, based on the IoT reference model layering [ITU-T Y.4000]. The following clauses describe the facilities of the three layers, as well as the cross-layer facilities of this framework.

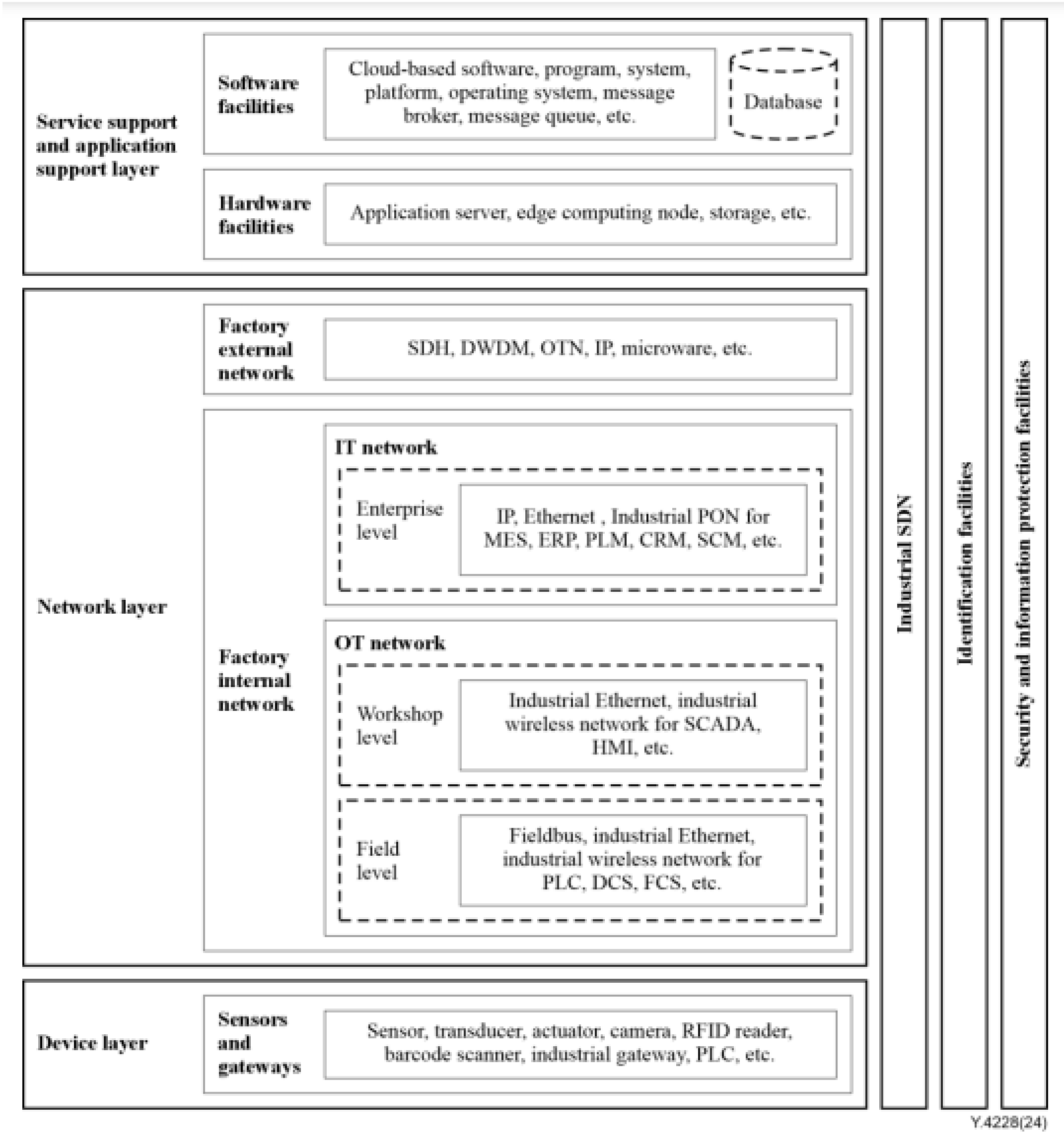

Figure 6: Conceptual framework of the IIoT infrastructure from the IoT

[Source: ITU-T Y.4228][8]

Device Layer

Due to the many communication technologies in the industrial network, the relevant communication media in the IIoT infrastructure physical layer are very diverse. The devices connected in the industrial network are not only personal computers (PCs), printers and other equipment, but also industrial control and management equipment, such as industrial PCs, human machine interface (HMI), programmable logic controllers (PLCs), motion controllers, remote terminals, and radio frequency identification (RFID) equipment. These devices work at different layers or across multiple layers of the open systems interconnection (OSI) [b-ITU-T X.200] reference model, provide data in standardized or non-standardized format, receive control and

[8] https://www.itu.int/ITU-T/recommendations/rec.aspx?id=16053

adjustment signals from the upper layers, and perform comprehensive sensing and control of relevant hardware and processes in the industrial production environment.

These devices can be distinguished into sensors and gateways, which directly interact with machines, robotics, environment equipment and other field facilities for smart manufacturing production.

Network Layer

The network provides comprehensive interconnection of people, machines and things, in order to transport data among them, this being a basic function to fulfil the requirements of industrial applications. It promotes seamless flowing and integration of diverse industrial data.

The IIoT network connections involve different technical fields inside and outside the enterprise. Many networking technologies are used in the industrial field with related performance advantages in specific scenarios. However, these technologies with specific capabilities (such as many kinds of industrial fieldbuses) are designed and applied only in specific scenarios, and cannot meet the requirements of IIoT in terms of data interoperability and seamless integration

The overall goal of the network connectivity is to promote the interconnection between systems, unlock data from isolated systems or networks, and make data play a greater value for industry and cross industry applications.

The network layer consists of two sub-layers, the factory internal network sub-layer and the factory external network sub-layer [b-ITU-T Y.2623].

Service support and application support layer

The IIoT infrastructure part in the service support and application support layer consists of hardware facilities and software facilities.

These facilities as the infrastructure in the service support and application support layer provide capabilities of integration of users and resources (such as data and services) inside and/or outside the enterprise, and further provide capabilities of industrial data integration analysis, in order to support the various industrial applications. They are a critical foundation for building industrial ecosystems for smart manufacturing.

Industrial SDN

The industrial software-defined networking (SDN) [b-ITU-T Y.3300] uses network controllers to uniformly manage the network resources, so as to ensure the network quality of service (QoS) required by applications. The key mechanism of the industrial SDN is to manage and configure networking devices through software definition.

With the utilization of advanced networking technologies, such as SDN and network functions virtualization (NFV) [b-ETSI NFV], the network can be virtualized. In this perspective, an SDN-based network can have different logical slides, which provide network services with different service level agreements (SLAs) [b-ITU-T M.1301]. These network services can be rapidly deployed, adjusted and recycled with high quality of service (QoS) [b-ITU-T E.800] guarantees.

The industrial SDN is used throughout the device layer, the network layer and the service support and application support layer. The industrial SDN network is composed of terminal equipment in the device layer, programmable industrial SDN devices in the network layer and industrial SDN controllers in the service support and application support layer. A terminal equipment submits the data flow characteristics and transmission requirements to the appropriate industrial SDN controller(s) through the northbound interface. The industrial SDN controller(s) generates the forwarding rules of the industrial SDN network according to the received data flow characteristics and transmission requirements, and the forwarding rules are implemented in the programmable industrial SDN devices through the standardized southbound interface.

The IT network and the OT network in the enterprise are traditionally operated independently of each other, the topologies of both networks are rigid, and the cross-network information interaction and management are very difficult. The industrial SDN enables the deep integration of the IT network and the OT network in order to build a flexible and agile industrial network. The equipment and traffic in the IT network and the OT network can be uniformly monitored and managed.

Identification facilities

As one of the components of the IIoT infrastructure for smart manufacturing, the identification facilities provide identification capabilities for the identification of physical and logical resources.

In the device layer, a unique identifier (ID) can be used to register and identify different kinds of devices, services and applications. In the network layer, an ID-based network communication can be leveraged to provide authentication and authorization capabilities to ensure the integrity and security of the information exchange. In the service support and applications support layer, the ID can be used as an entry to resolve the attributes, capabilities and services that are linked with the corresponding devices.

Security and information protection facilities

The security and information protection facilities provide security and information protection capabilities for the different enterprise functions, including device authentication and authorization, physical security, functional security and information security.

Those facilities are mainly used to protect various physical or virtual industrial resources, data analysis services, development kits, industrial applications, etc. They run through all the three layers of the IIoT infrastructure and address the different dimensions of security, including reliability, confidentiality, integrity, availability and information protection.

2. Communication Technologies in IoT/M2M domain

Various types of communication technologies are used in M2M/ IoT domain depending upon the coverage, power, QoS, specific use case requirement etc. These communication technologies maybe categorized to work in Personal/Neighborhood/Local/Wide Area Network i.e. PAN/NAN/LAN/WAN depending upon the coverage distance. Figure 7 describes the communication technology used in M2M/IoT domain.

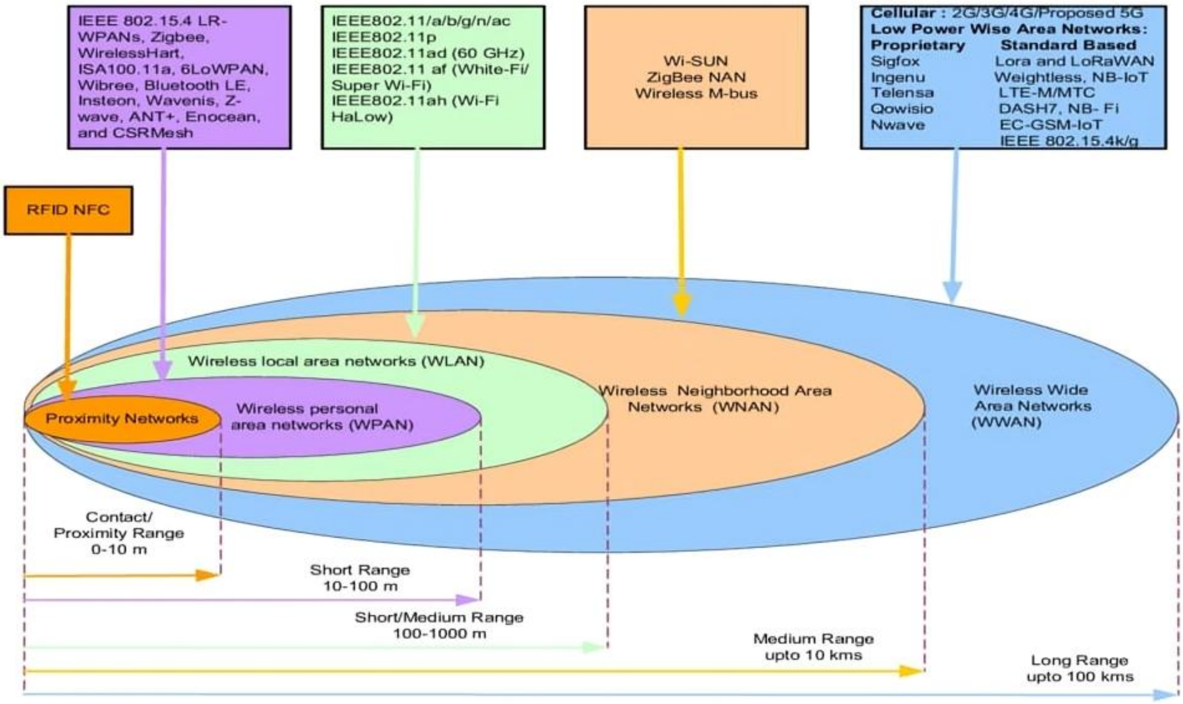

Figure 7: Communication Technologies in M2M/IoT domain

Technical Report on ***Communication technologies in M2M/ IoT domain***[9] was released in 2017. This report covers Cellular Technologies (2G, 3G, 4G i.e. up to LTE 3GPP Release14), Low power wireless communication technologies (NFC, RFID, Bluetooth, ZigBee, etc.), Low power wide area network technologies (LPWAN – cellular/non-cellular), Wi-Fi [IEEE 802.11 a, b, g, n, ac], DSRC (802.11p), wire line (PLC, DSL, FTTH) etc. and the related use cases.

Due to advancement in technology, further study was done and the Technical Report on ***Emerging Communication Technologies and Usecases in IoT domain***[10] was released in November 2021. This report covers 5G, Wi-Fi 6, Wi-Fi 6E, WiFi HaLow, Bluetooth Mesh and some important use cases such as Intelligent transport system (Connected vehicles, C-V2X etc.), Private Industrial Network (Smart factories, Industry 4.0), Smart homes etc.

IoT devices typically utilize wireless communication technologies, although they may also be connected via wireline. Some of the examples of the IoT devices may include smart camera,

[9] https://tec.gov.in/pdf/M2M/Communication%20Technologies%20in%20IoT%20domain.pdf

[10] https://tec.gov.in/pdf/M2M/Emerging%20Communication%20Technologies%20&%20Use%20Cases%20in%20IoT%20domain.pdf

smartwatch, smart meters, tracking devices etc. IoT gateways may include POS machines, smartphones, Wi- Fi routers etc. Further, the data collected from IoT devices is transferred to the cloud either directly or through an IoT gateway for storage and analysis purpose, for taking informed decisions.

2.1. Cellular Technologies

The GSM standard originally described a digital, circuit-switched network optimized for full duplex voice telephony. This expanded over time to include data communications, first by circuit-switched transport, then by packet data transport via General Packet Radio Service (GPRS), and Enhanced Data Rates for GSM Evolution (EDGE). 2G networks developed as a replacement for first generation (1G) analog cellular networks. Subsequently, the 3rd Generation Partnership Project (3GPP) developed third-generation (3G) UMTS standards, followed by the fourth-generation (4G) LTE Advanced and the fifth-generation 5G standards.

The figure 8 shows the evolution of cellular technology, illustrating the progression from 1G, which provided basic voice services, to 2G that introduced digital voice and text messaging. It then progresses to 3G, which enhanced data transfer speeds and enabled mobile internet access. The figure continues with 4G, offering high-speed data and improved multimedia capabilities, 5G, which brings ultra-fast speeds, low latency, and supports a massive number of connected devices for advanced applications like IoT and smart cities. Finally, 6G, which is still under development, aims to deliver even greater speeds, virtually instantaneous connectivity, and advanced applications such as holographic communication, pervasive AI, and more immersive digital experiences, setting the stage for the future of cellular technology.

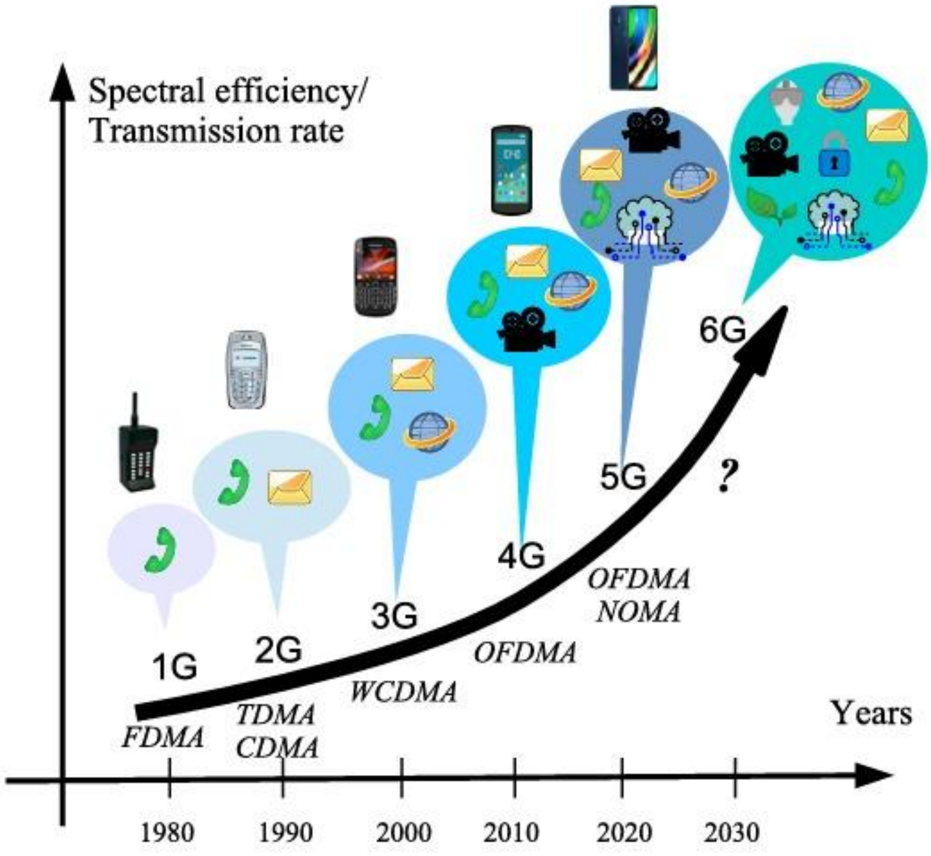

Figure 8: Evolution of Cellular Technologies

[Source: IEEE][11]

2.1.1. 4G-LTE/ LTE-Advanced

LTE, originally introduced in 3GPP Release 8, was developed to provide faster mobile broadband access, offering a generational performance leap over 3G. The major change in LTE compared to previous systems was the adoption of an all-IP approach. LTE Advanced (3GPP release 10, 11,12) evolved to optimize for better mobile broadband experience, enabling gigabit-class throughput with the introduction of advanced techniques, such as carrier aggregation and higher-order MIMO. Some applications of LTE are Remote Monitoring, Data Collection and Analysis, Surveillance Systems, aerial surveys by using drones/ UAV's etc.

3GPP Release 13 introduced a suite of new narrowband technologies optimized for the IoT. LTE-M (eMTC) enables the broadest range of IoT capabilities and NB-IoT scales down further in cost and power for low-end IoT use cases. Low power consumption and long-range capabilities make NB-IoT well-suited for applications in remote monitoring and data acquisition in industrial

[11] C. A. Gutierrez, O. Caicedo and D. U. Campos-Delgado, "5G and Beyond: Past, Present and Future of the Mobile Communications," in IEEE Latin America Transactions, vol. 19, no. 10, pp. 1702-1736, Oct. 2021, doi: 10.1109/TLA.2021.9477273.

environments, supporting data-driven decision-making and process optimization in Industry 4.0 applications.

2.1.2. 5G/ IMT 2020

5G is an emerging communication technology introduced in 3GPP Release 15. 5G provides faster speed, lower latency, and wider coverage as shown in figure 9.

- Mobile IoT/ Massive IoT/ LPWAN: improved network coverage, long device operational life time and a high density of connections. This is also known as Massive Machine Type Communication (mMTC).
- Critical communications: high performance, ultra-reliable, low latency for industrial IoT and mission critical applications. This is also known as Ultra Reliable Low Latency Communications (URLLC).
- Enhanced Mobile Broadband: Improved performance and a more seamless user experience accessing multimedia content for human-centric communications. This is also known as Enhanced Mobile Broadband (eMBB).

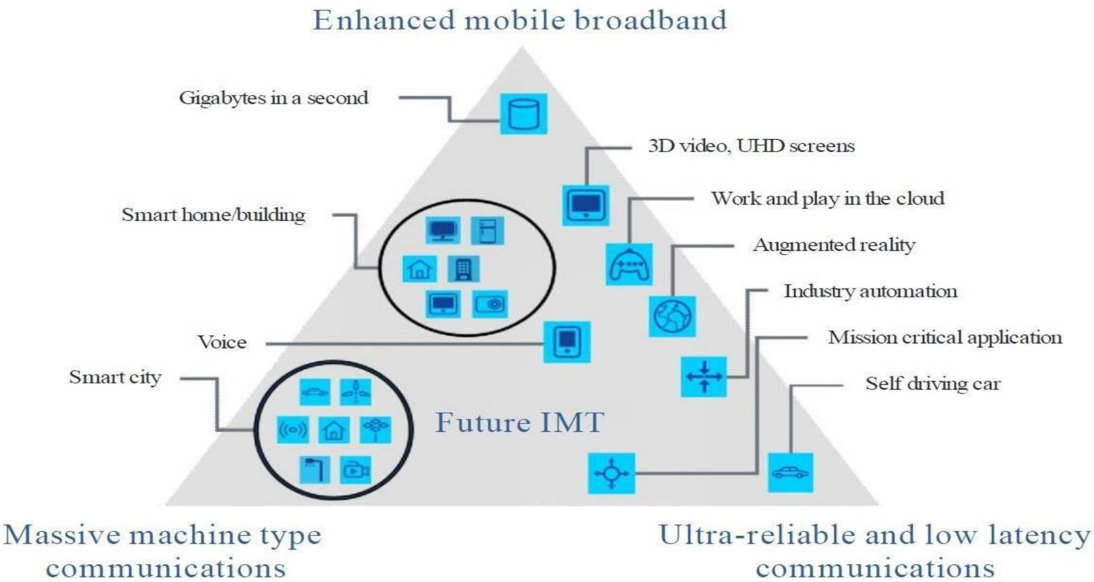

Figure 9: 5G Use Case Scenarios

[Source: ITU-R Rec. M.2083][12]

5G and beyond technologies are envisaged to expand on the IMT-Advanced performance requirements like Peak data rate, User experienced data rate, Spectrum efficiency, Mobility, Latency, Connection density, Network energy efficiency, and Area traffic capacity as depicted in Figure 10.

[12] https://www.itu.int/rec/R-REC-M.2083-0-201509-I/en

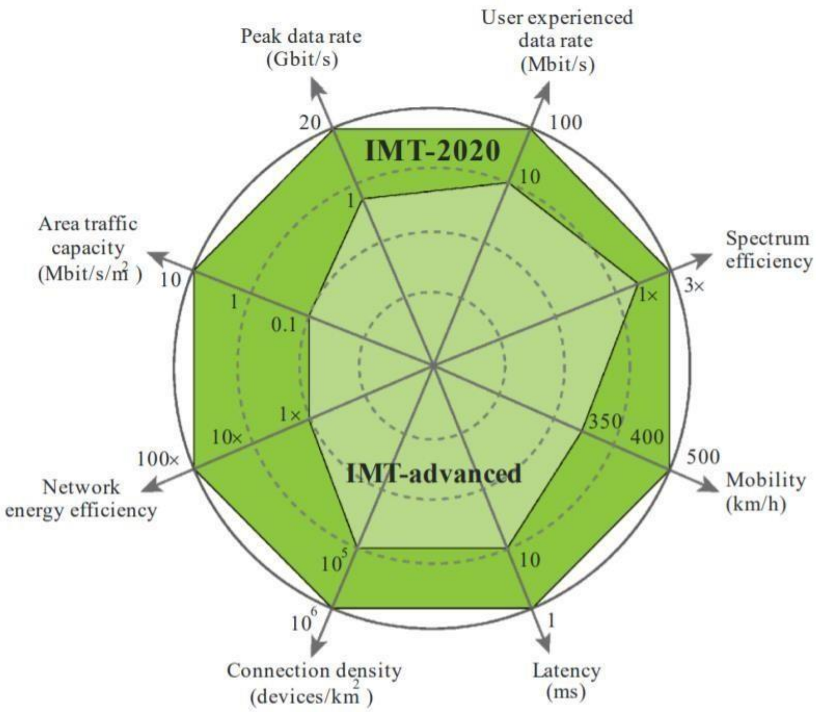

Figure 10: Enhancement of key capabilities from IMT-Advanced to IMT-2020 (4G to 5G)

[Source: ITU-R M.2083][13]

Some other key aspects of 5G/ IMT-2020 are detailed below-

Network Slicing: 5G introduces network slicing, allowing the network to be divided into multiple virtual networks to accommodate diverse use cases with varying requirements for latency, bandwidth, and reliability.

Massive MIMO (Multiple Input Multiple Output): Increased Antenna Arrays, 5G networks leverage massive MIMO technology, involving a large number of antennas at both base stations and user devices. This enhances data rates, spectral efficiency and overall network capacity.

Network function virtualization (NFV): It is cloud-native architecture, allowing network components to be virtualized and deployed as software-defined functions.

New Radio (NR): 5G NR specification defines how 5G NR edge devices (smart phones, embedded modules, routers, and gateways) and 5G NR network infrastructure (base stations, small cells, and other Radio Access Network equipment) wirelessly transmit data. 5G NR is the global standard for a unified, more capable 5G wireless air interface for radio communication. NR supports both non-standalone (NSA) and standalone (SA) deployment options. It is delivering significantly faster and more responsive mobile experiences.

2.1.3. RedCap (Reduced Capability) / NR Lite / NR light

3GPP Release 17 introduced 5G RedCap in 5G NR, also termed NR-Light, a new standard for

[13] https://www.itu.int/rec/R-REC-M.2083-0-201509-I/en

devices known as reduced capability (RedCap) devices. 5G RedCap is one of the latest advancement in cellular technology within the IoT landscape, catering to a range of use cases thus adding a new dimension to IoT connectivity. It is designed to address the use cases in between the high speed Enhanced mobile broadband (eMBB), the ultra-reliable low latency communications (uRLLC) and the low throughput and battery efficient Massive Machine-Type Communication (mMTC) technologies. This innovation represents a bridge between the extremes in 5G technology, as shown in figure 11 below.

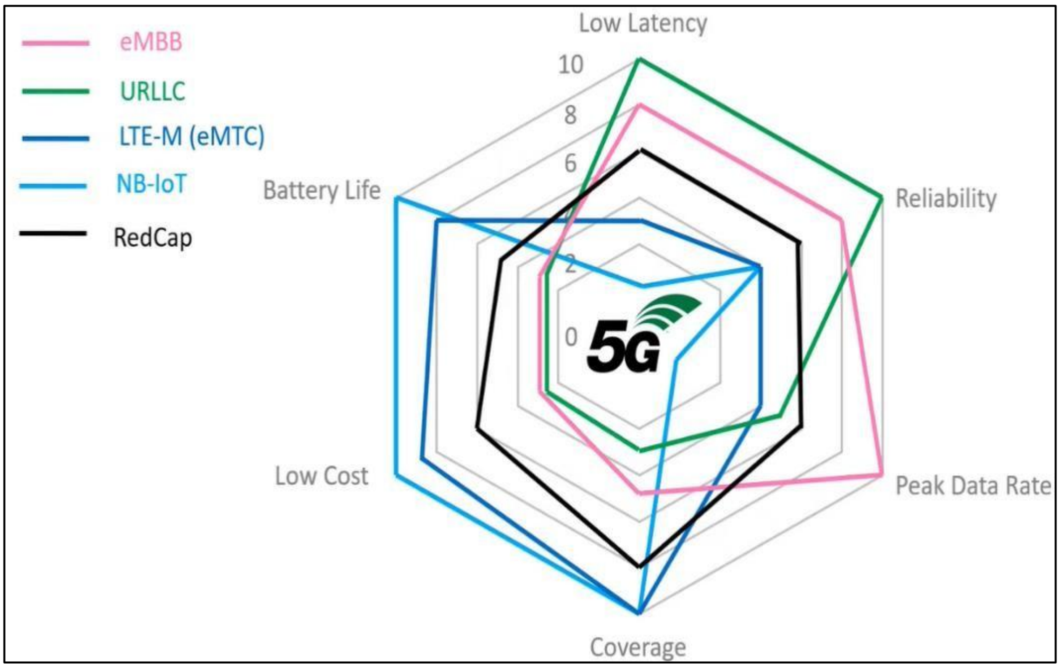

Figure 11: 5G Spider Diagram combined with RedCap
[Source: 3G4G.CO.UK][14]

For massive IoT services, narrowband IoT (NB-IoT) and enhanced machine type communication (eMTC)/LTE-M devices prioritize low power consumption and the lowest complexity for wide-area deployments (LPWA), while enhanced ultra-reliable, low-latency communication (eURLLC) devices deliver on the most stringent use case requirements in industry. But there exists an opportunity to address a broad range of mid-tier applications more efficiently, with capabilities between these extremes.

Different types of NR RedCap UEs / Devices may include video surveillance, Industrial Wireless Sensors i.e. CO_2 sensors, Pressure sensors, Motion sensors, Fluid sensors, etc. It may also include Low-end Wearables.

2.1.4. Ambient IoT

3GPP Release 19 introduced advance feature in 5G known as Ambient IoT, which is an emerging paradigm that extends traditional IoT by embedding connectivity and sensing capabilities into

[14] https://www.3g4g.co.uk/Training/beginners0039.html

everyday objects and environments, making them "ambiently" aware and capable of generating and transmitting data without human intervention or continuous power sources.

Unlike conventional IoT systems, which typically rely on active power and intentional deployment, Ambient IoT integrates passive or low-energy components (e.g., battery-free sensors, printed electronics, RFID, BLE tags) into materials, packages, and assets, enabling ubiquitous and cost-effective sensing at scale.

Key Features of Ambient IoT

- **Low/No Power Operation**: Uses technologies like energy harvesting or near-field communication to function without batteries.
- **Massive Scale**: Supports millions of connected items across an environment, such as tools, containers, components, and finished goods.
- **Embedded Intelligence**: Adds traceability and context-awareness directly into the objects themselves.
- **Edge Integration**: Can seamlessly transmit data to local gateways, edge devices, or cloud platforms using lightweight protocols.

In the context of Industry 4.0, Ambient IoT enables highly connected systems where not just machines and equipment, but even individual items and materials can be tracked and managed in real time. One key application is smart inventory and materials tracking, where Ambient IoT tags attached to parts, pallets or tools provide real-time information about their location, usage and movement on the shop floor. This helps improve internal logistics, reduces time spent searching for items and enhances production flow.

Another important use is in supply chain transparency. Ambient IoT makes it possible to track items individually throughout the global supply chain, from the sourcing of raw materials to final delivery. This improves accountability, reduces losses and ensures compliance with quality and regulatory standards.

Ambient IoT also plays a vital role in condition monitoring and quality control. By embedding environmental sensors into packaging or components, it becomes possible to continuously monitor conditions like temperature, vibration or humidity. This is especially critical in industries like pharmaceuticals, electronics and food, where product quality depends on stable environmental conditions.

Ambient IoT supports sustainability and the circular economy. With battery-free and printable sensors, it reduces electronic waste and promotes green manufacturing. It also helps track the lifecycle and usage of products, enabling more efficient reuse, recycling and waste reduction.

2.1.5. 6G and beyond

As we advance in the era of Industry 4.0, the development of 6G technology is poised to be a game-changer, extending the capabilities of connectivity and transforming various sectors in unprecedented ways. While 5G has already brought significant improvements with its high speeds, low latency and capacity for massive device connectivity, 6G is set to push these boundaries even further.

6G promises ultra-high data transfer speeds, potentially exceeding 100 Gbps, which will enable real-time data processing and communication. This leap in speed will support applications requiring instantaneous responses, such as remote surgery and advanced robotics. Additionally, 6G aims to offer ubiquitous coverage, addressing current limitations by combining terrestrial and non-terrestrial networks to ensure seamless connectivity in urban, rural, and even underwater environments. The integration of Artificial Intelligence (AI) into 6G networks will enhance network management, optimization and automation, allowing networks to dynamically adapt, predict and resolve issues with unprecedented efficiency.

The advancements brought by 6G will have profound implications for Industry 4.0. Enhanced connectivity and data speeds will bolster the development of smart factories, autonomous systems, and IoT. In smart manufacturing, 6G will facilitate real-time monitoring, predictive maintenance and optimized production processes, leading to greater efficiency and reduced downtime. Autonomous vehicles will benefit from the low latency and high-speed data of 6G, enabling more accurate decision-making for navigation and safety. Additionally, advanced robotics will gain from 6G’s capabilities, performing complex tasks with greater precision and coordination.

Though 6G is still in its nascent stages, its potential to reshape Industry 4.0 is clear. As research and deployment of 6G progress, industries should prepare to harness its capabilities to drive innovation, enhance operational efficiency and explore new business opportunities. The advent of 6G will mark a significant milestone in technological evolution, setting the stage for the next generation of connectivity and industrial transformation.

2.2. Low Power Wide Area Network (LPWAN) Technologies

2.2.1. Cellular LPWAN Technologies

NB-IoT and LTE-M

3GPP introduced technologies such as NB-IoT and LTE-M to address requirements of IoT applications, with a specific emphasis on long-battery life, low complexity, including requirements on support of large number of devices, low device cost, and coverage in challenging locations.

There is a good compatible and complementary relationship between LTE-M and NB-IoT since both are based on the LTE platform. The primary difference is their operational bands. LTE-M operates at 1.4 MHz in- band with LTE, whereas NB-IoT can operate at 180 kHz in-band, in guard band, or in a standalone mode. This allows NB-IoT to repurpose GSM frequency structure as well. Retuning of the antenna and provisioning the frequencies in the eNodeB can support bothtechnologies.

Major areas in which LTE-M and NB-IoT differ include bandwidth support, latency, power consumption and device cost. LTE-M has higher throughput with lower latency and battery useis optimized accordingly. The battery life of a LTE-M device can be lower than that of NB-IoT andpower consumption is more at comparatively high data rates as opposed to NB-IoT which consumes less power at low data rates. LTE-M can also carry voice for applications such as residential security systems. LTE-M and NB-IoT both support the 5G connection density requirement of 1,000,000 connected devices per km^2 with a service delivery within 10 seconds.

In summary, LTE-M and NB-IoT meet the IMT-2020 and 3GPP 5G requirements for Massive IoT and support seamless coexistence between NR, LTE-M and NB-IoT. This makes LTE-M and NB- IoT today's most prominent and futureproof 5G Massive IoT technologies.

Some of the key applications of NB-IoT and LTE-M are in smart cities (smart street lighting, waste management, environmental monitoring, and smart parking). The low-power characteristics make them suitable for long-term deployment in urban infrastructure, Agriculture, Industrial IoT, Healthcare, Smart Metering, Environmental Monitoring etc.

2.2.2. Non Cellular LPWAN Technologies

LoRaWAN

LoRaWAN, which stands for Long Range Wide Area Network, is a communication protocol designed for lowpower wide area networks (LPWANs) that offer long range and secure data transmission for M2M and IoT applications. LoRa is based on chirp spread spectrum modulation, which has low power characteristics like FSK modulation but can be used for long range communications. LoRa technology enables efficient, low-cost, and low-energy communication for devices that need to transmit small amounts of data over considerable distances. LoRa can be used to connect sensors, gateways, machines, devices, etc. wirelessly to the cloud.

LoRa Technologies operates in different frequency bands in different regions; in India it operates in the frequency band of 865 to 868 MHz. Its distinctive features include an impressive communication range, covering several kilometers in rural environments and reaching a few hundred meters in urban areas. LoRa devices are characterized by their low power consumption, ensuring extended battery life for connected devices, making it well-suited for applications in remote or challenging locations where frequent battery replacements are impractical.

The network architecture of LoRaWAN is shown in figure 12 below:

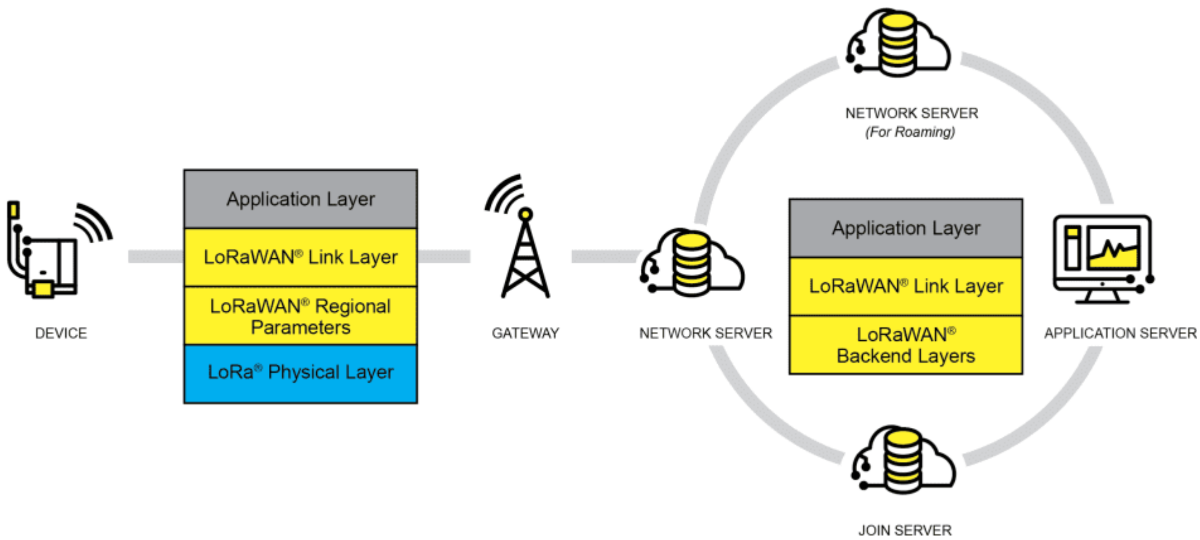

Figure 12: LoRaWAN Network Architecture
[Source: LoRa-Alliance][15]

2.3. Low Power Short Range Technologies

2.3.1. Wi-Fi/ IEEE 802.11 Based Technologies

Wi-Fi is a family of wireless network protocols based on the IEEE 802.11 family of standards, which are commonly used for local area networking of devices and Internet access, allowing nearby digital devices to exchange data by radio waves. Wi-Fi is a trademark of the Wi-Fi Alliance. Wi-Fi most commonly uses the 2.4 GHz and 5 GHz radio bands; these bands are subdivided into multiple channels. Channels can be shared between networks, but within range only one transmitter can transmit on a channel at a time.

Wi-Fi compatible devices can connect to the Internet via a WLAN network and a wireless access point. Such an access point (or hotspot) has a range of about 20 meters indoors and a greater range outdoors. Hotspot coverage can be as small as a single room with walls that block radio waves, or as large as many square kilometers achieved by using multiple overlapping access points. Various IEEE 802.11 standards are mentioned in table below:

Table 1: Various IEEE 802.11 Standards

IEEE Standard	Frequency Bands	Max Speed
802.11a	5 GHz	54 Mbit/s
802.11b	2.4 GHz	11 Mbit/s
802.11g	2.4 GHz	54 Mbit/s

[15] https://lora-alliance.org/about-lorawan-old/

802.11n	2.4 GHz and 5 GHz	600 Mbit/s
802.11ac	5 GHz	3.5 Gbit/s

Wi-Fi is an important communication protocol pertaining to M2M communication as in several scenarios Wi-Fi hotspots are potentially the gateways for most sensor nodes.

2.3.2. Wi-Fi 6

Wi-Fi 6, or IEEE 802.11ax, stands as the latest evolution in wireless technology, surpassing Wi-Fi 5 (802.11ac). This advanced standard introduces significant enhancements to wireless connectivity, delivering higher data rates through use of wider channels, advanced modulation techniques, and overall efficiency improvements. Operating in both the 2.4 GHz and 5 GHz frequency bands, Wi-Fi 6 ensures backward compatibility while providing a migration path for devices from 802.11n and 802.11ac.

IEEE802.11ax focuses on better efficiency, capacity and performance as compared to previous technologies of Wi-Fi family, thus providing 4x improvements in average throughput per user and better user experience even for dense indoor/outdoor deployments such as airports, railway stations, shopping malls, stadiums, homes, school campuses.

Key features include Orthogonal Frequency Division Multiple Access (OFDMA), dividing a channel into smaller sections to enable simultaneous communication with multiple devices, enhancing efficiency and reducing latency.

Several nations around the globe are making 6 GHz band available for unlicensed use. Wi-Fi 6E extends Wi-Fi 6 to the 6 GHz band. Wi-Fi 6 operation in the 6 GHz frequency band enables Wi-Fi to continue delivering positive experiences for the most bandwidth-intensive applications.

2.3.3. Bluetooth Low Energy

Bluetooth Low Energy (BLE), also known as Bluetooth Smart, is a wireless communication technology designed for short-range communication with low power consumption. It is a part of the Bluetooth wireless communication standard and is specifically optimized for energy efficiency, making it well suited for a wide range of battery-powered devices and applications in the Internet of Things (IoT). BLE devices operate in the unlicensed 2.4 GHz ISM band. A frequency hopping transceiver is used to combat interference and fading.

Unlike the classical Bluetooth which uses 79: 1-MHz-wide channels, BLE uses 40: 2-MHz wide channels. Three of these channels, which are located between commonly used wireless local area network channels, are used for advertising and service discovery and are called advertising channels. The remaining 37 data channels are used to transfer the data.

2.3.4. Near Field Communication

Near Field Communication (NFC) is a short-range wireless communication technology that enables seamless and secure data exchange between devices in close proximity, typically within a few centimeters. Operating at the radio frequency of 13.56 MHz, NFC facilitates communication between devices by simply bringing them close together or tapping them. NFC is commonly integrated into smartphones, credit cards, and various electronic devices, making it a convenient and versatile technology for a range of applications. The data rate is 106 Kbit/s to 424 Kbit/s. NFC is an offshoot of radio-frequency identification (RFID) with the exception that NFC is designed for use by devices within close proximity to each other. NFC requires 4 cm or less to initiate the connection with the tag. There are two variants of NFC. One is the Transceiver and the other is Tag.

NFC operates in two modes: active and passive. Transceivers are active devices which need power to operate. An active NFC device, such as a smartphone, would not only be able to collect information from NFC tags, but it would also be able to exchange information with other compatible phones or devices and could even alter the information on the NFC tag if authorized to make such changes.

Tags are the passive devices and work on the principle of inductive coupling when the tag is brought near a transceiver. NFC allows transferring small amount of data between transceiver and tags. There are three mode of data transfer in NFC:

- **Peer to Peer communication**: Peer-to-peer mode enables two NFC-enabled devices to communicate with each other to exchange information and share files.

- **Card Emulation**: Card emulation mode enables NFC-enabled devices to act like smart cards, allowing users to perform transactions such as purchases, ticketing, and transit access control with just a touch.

- **Reader/ Writer**: Reader/ writer mode enables NFC-enabled devices to read information stored on inexpensive NFC tags embedded in smart posters and displays, providing a great marketing tool for companies. Examples include reading timetables, tapping for special offers, and updating frequent flyer points.

Figure 13 below highlights some of the common applications of NFC technology in everyday scenarios:

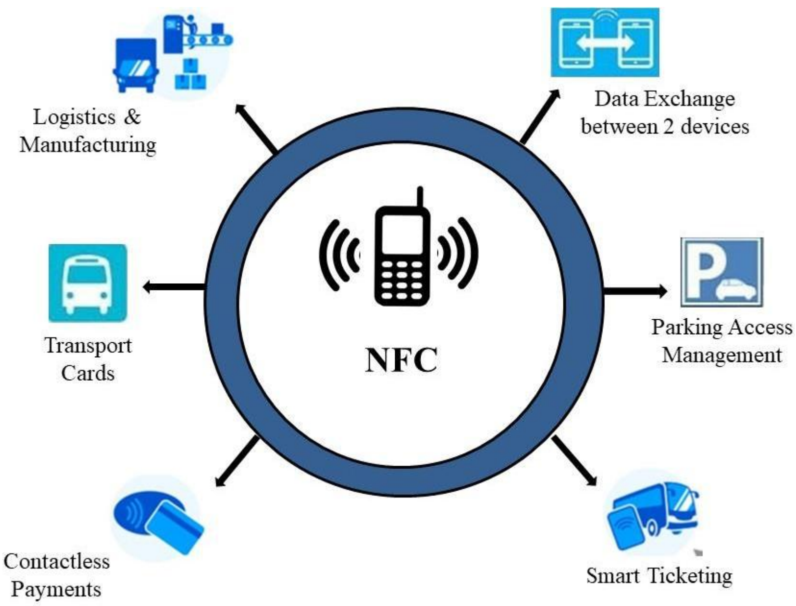

Figure 13: Applications of NFC

2.3.5. Radio Frequency Identification

Radio Frequency Identification (RFID) is a type of wireless communication that uses electromagnetic or electrostatic coupling in the radio frequency spectrum to uniquely identify an object, animal, or human.

A typically RFID system consists of tags (transmitters/ responders) and readers (transmitters/receivers). The tag is a microchip connected with an antenna, which can be attached to an object as the identifier of the object. The RFID reader communicates with the RFID tag using radio waves. The RFID tags come in various forms, including passive, active, and semi-passive, each designed for specific use cases.

Passive RFID Tags: These tags rely on the energy emitted by the RFID reader to transmit data. They are cost-effective and widely used in applications such as inventory management and access control.

Active RFID Tags: Active tags have their own power source, enabling them to transmit data over longer distances and in real-time. These are suitable for applications requiring continuous monitoring, like tracking the location of high-value assets.

Semi-Passive RFID Tags: Combining elements of both passive and active tags, semi-passive tagsuse their own power source for data transmission but rely on the RFID reader for energy to power other functionalities. This strikes a balance between extended range and power efficiency.

The functions of RFID system generally include three aspects: monitoring, tracking, and supervising. The most interesting and successful applications include supply chain management, production process control, and objects tracking management. Few RFID applications are shownin Figure 14 below:

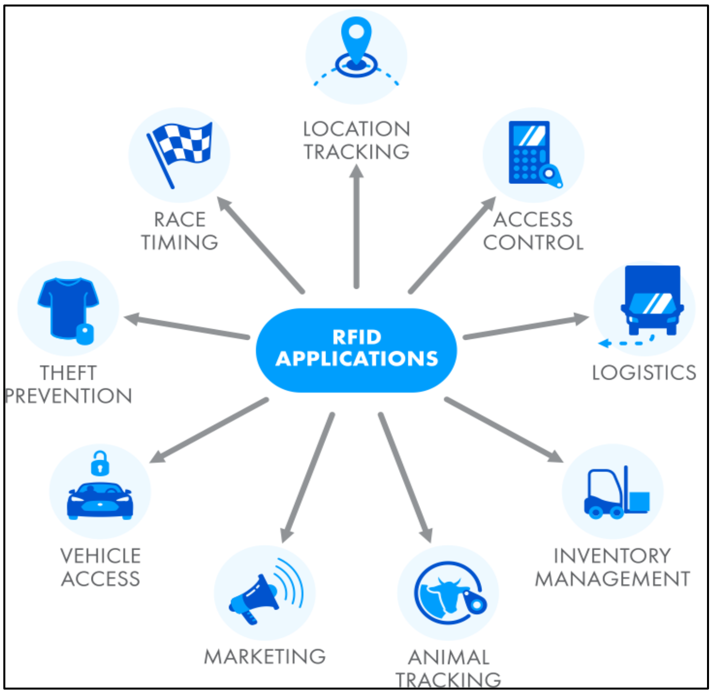

Figure 14: Applications of RFID

2.3.6. ZigBee

ZigBee is a wireless mesh network standard characterized by its affordability and low-power features, primarily designed for the widespread deployment of devices with extended battery life in wireless control and monitoring applications. ZigBee devices have low latency, resulting reduction in average current consumption. ZigBee mostly operates in the ISM band i.e. 2.4 GHz worldwide including India.

As a globally recognized communication protocol, ZigBee is established by a significant task force operating under the IEEE 802.15 working group. It builds upon the physical layer and media access control defined in IEEE standard 802.15.4 for low-rate Wireless Personal Area Networks (WPANs). ZigBee supports various network topologies, such as star, mesh, and cluster tree configurations, ensuring adaptability to diverse application requirements. One of its key strengths lies in its commitment to low-power consumption, making it suitable for battery- powered devices and applications requiring intermittent data transmission.

3. Enabling Technologies for Industry 4.0

3.1. Artificial Intelligence (AI) and Machine Learning (ML)

As Artificial Intelligence (AI) is an interdisciplinary field, often seen as a branch of computer science, focused on creating models and systems that perform functions typically associated with human intelligence, such as reasoning and learning [ITU-T F.749.13]. AI is characterized by machine intelligence designed to mimic human-like cognitive functions, acting as a cognitive engine that facilitates analysis and decision-making based on data from various sources. By processing this data, AI derives meaningful insights, a capability increasingly integrated into everyday devices like fitness trackers, Google Home, and Amazon Alexa.

The figure 15 below illustrates the concept of Artificial Intelligence:

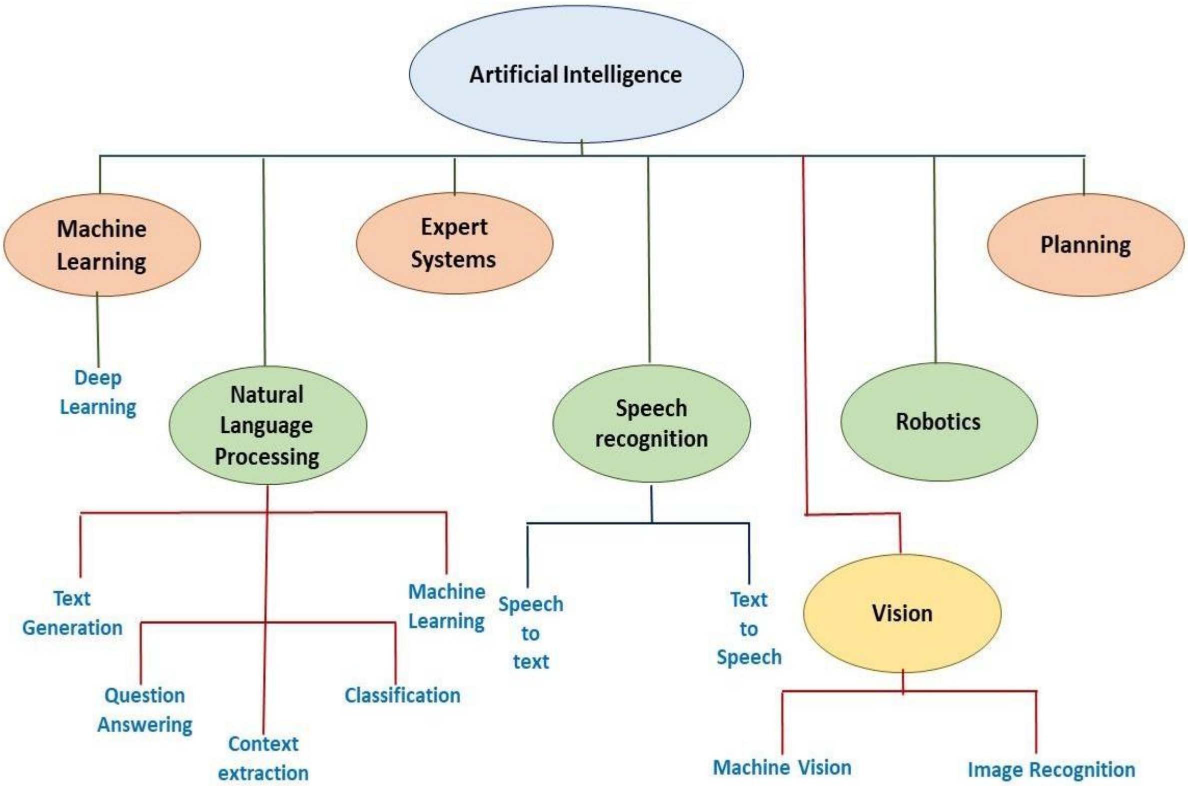

Figure 15: Artificial Intelligence

Developing an AI involves implementing appropriate algorithms, utilizing various forms of data such as documents, audio, video, or images. It entails training the system through the integration of algorithms with the provided data, necessitating iterative refinement until the training produces a satisfactory outcome. This entire sequence must be repeated multiple times to achieve optimal results.

Artificial Intelligence in IoT involves embedding AI technologies, such as machine learning, deep learning, and natural language processing, into IoT devices, sensors, and platforms to enable smart decision-making, learning, and autonomous actions. It represents the integration of AI capabilities into IoT devices and systems, enabling these devices to analyze data, make decisions, and perform tasks autonomously. It aims to enhance the intelligence and efficiency of IoT deployments by leveraging AI algorithms and techniques.

In the context of Industry 4.0, AI serves as a pivotal technology driving smart manufacturing and industrial automation. AI systems are implemented through appropriate algorithms and the utilization of various data forms, such as documents, audio, video, and images. Training these systems involves iterative refinement to achieve optimal outcomes, often requiring repeated cycles of algorithm integration and data processing.

Applications of AI in Industry 4.0

1. **Smart Factories:** AI enables smart factories by integrating machine learning, deep learning, and natural language processing into industrial equipment and systems. This integration facilitates smart decision-making, learning, and autonomous actions within manufacturing environments.
2. **Predictive Maintenance:** AI analyzes real-time data from sensors embedded in machinery to predict equipment failures before they occur. Machine learning algorithms detect patterns and anomalies that indicate potential issues.
3. **Supply Chain Optimization:** AI algorithms optimize supply chain operations by forecasting demand, managing inventory, and optimizing logistics. This ensures that resources are used efficiently and that products are delivered on time.
4. **Quality Control and Assurance:** AI-driven automated inspection systems and analytics ensure products meet stringent standards and regulations. AI detects defects and deviations in real-time, maintaining high-quality production.
5. **Human-Robot Collaboration:** AI enhances the collaboration between humans and robots, with robots learning from human actions and adapting their behavior. Augmented Reality (AR) provides real-time information and guidance to workers.

The collaboration of AI and Industry 4.0 finds applications in various sectors, including healthcare for remote monitoring and predictive analytics, smart agriculture for precision farming, and energy management for optimizing consumption. This synergy extends to smart cities, where AI-powered systems contribute to efficient traffic management and public services. Overall, the convergence of AI and Industry 4.0 holds tremendous potential, ushering in a new era of intelligent, adaptive, and efficient industrial systems.

Machine learning

Machine Learning is essentially the scientific approach enabling machines to interpret, process, and analyze data for addressing real-world issues. It is simply a subset of Artificial Intelligence (AI) that imparts machines with the capacity to autonomously learn and enhance their performance through experience, without explicit programming. In essence, machine learning involves empowering machines to think and solve problem. This discipline relies on vast amounts of both structured and unstructured data, ensuring that machine learning models deliver accurate results or predictions based on the acquired knowledge. In Industry 4.0, various machine learning models are employed for predictive maintenance, quality control, supply chain optimization, and other applications.

Machine learning is indispensable in Industry 4.0, driving efficiency, innovation, and automation in manufacturing and industrial operations. By transforming data into actionable insights, ML enhances various aspects of industrial processes, making it a fundamental enabler of the next industrial revolution. Its application across different domains ensures smarter, more resilient, and more adaptive manufacturing systems, positioning companies to thrive in a competitive global market.

3.2. Cloud Computing

As per [ITU-T Y.3500][16], Cloud Computing is Paradigm for enabling network access to a scalable and elastic pool of shareable physical or virtual resources with self-service provisioning and administration on demand. NOTE – Examples of resources include servers, operating systems, networks, software, applications, and storage equipment.

Cloud computing can be defined as a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.

Cloud computing offers several models:

- **Infrastructure as a Service (IaaS):** Provides virtualized computing resources over the internet.
- **Platform as a Service (PaaS):** Offers hardware and software tools over the internet, primarily for application development.
- **Software as a Service (SaaS):** Delivers software applications over the internet, on a subscription basis.

Companies have already embraced cloud-based software for various enterprise and analytics applications. However, with the advent of Industry 4.0, there will be a growing need for enhanced data sharing across different sites and organizational boundaries for production-related activities. As cloud technology continues to advance, achieving response times of just a few milliseconds, the shift towards deploying machine data and functionalities to the cloud will accelerate. This transformation will enable the development of more data-driven services for production systems. Moreover, even systems responsible for monitoring and controlling processes are expected to transition to cloud-based solutions.

Manufacturing Execution System (MES) vendors have already begun offering cloud-based solutions, reflecting this trend. By leveraging cloud technologies, companies can achieve greater flexibility, scalability, and efficiency in their production operations. Additionally, cloud-based solutions facilitate real-time data analysis and decision-making, enhance collaboration across the supply chain, and reduce the need for on-premises infrastructure. This shift not only optimizes production processes but also supports the integration of advanced technologies such as artificial

[16] https://www.itu.int/rec/T-REC-Y.3500-201408-I

intelligence (AI), machine learning (ML), and the Internet of Things (IoT) in manufacturing environments, driving innovation and competitiveness in the Industry 4.0 era.

3.3. Edge Computing

Edge computing plays a crucial role in Industry 4.0 and smart manufacturing by bringing computation and data processing closer to the source of data generation. This proximity enables real-time decision-making, reduces latency, enhances security, and minimizes bandwidth usage. In smart manufacturing environments, edge computing allows machines and devices to process data locally, enabling instant responses to critical situations, predictive maintenance, and quality control without relying on cloud connectivity. This decentralized approach is particularly valuable when dealing with time-sensitive operations or when working in areas with limited network connectivity.

Edge computing and cloud computing serve complementary roles in modern industrial environments, each with distinct advantages. Edge computing processes data locally, offering millisecond-level response times, reduced bandwidth usage, and continued operation during internet outages, making it ideal for real-time applications like quality control and emergency responses. In contrast, cloud computing provides virtually unlimited scalability, lower initial costs, and centralized data management, but comes with higher latency and depends on stable internet connectivity. While edge computing keeps sensitive data within the facility and reduces transmission costs, cloud solutions excel at enterprise-wide analytics and cross-facility coordination. Most successful Industry 4.0 implementations use a hybrid approach – for example, using Siemens SIMATIC IPC Edge for real-time machine monitoring while leveraging cloud platforms like MindSphere for broader analytics and long-term storage. This combination ensures both immediate operational efficiency and comprehensive data analysis capabilities, creating a robust foundation for smart manufacturing.

Edge AI

Edge AI is bringing the artificial intelligence closer to the machines or the shop floor. AI can be executed in the local devices connected directly to the machines or in the gateway. This reduces the round trip to the cloud the make decisions. However, the knowledge is synthesized at the cloud and then shared with the edge devices. Some use cases

- Improve quality control through instant image or sensor analysis
- Monitor energy consumption and optimize usage
- Enhance safety by spotting potential hazards on the floor
- Automate correction in previous process based on the outcome of this process.

Figure 16 describes the Edge AI Processing Cycle.

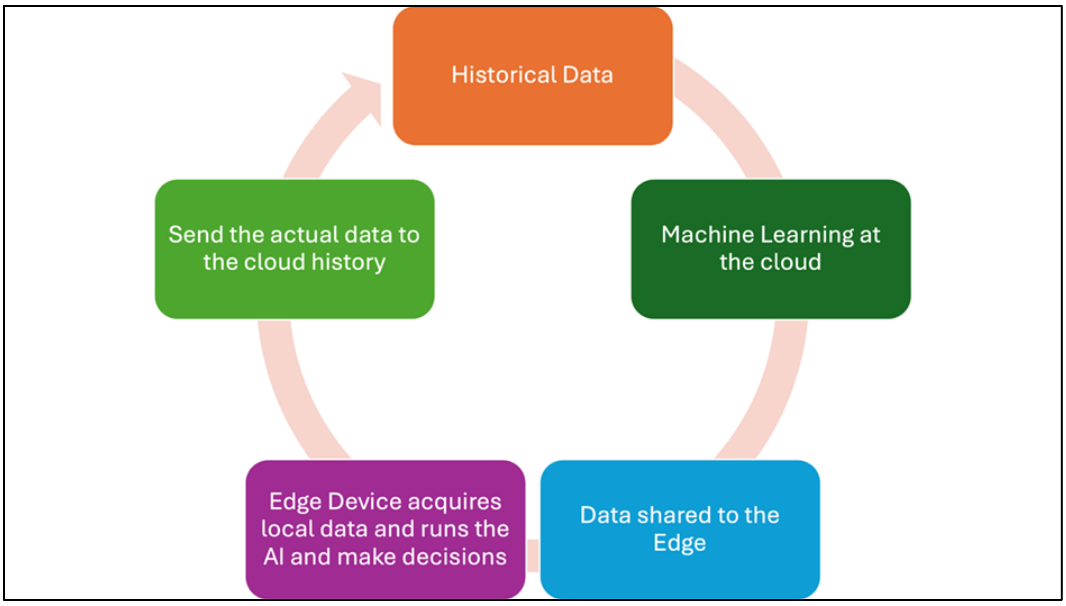

Figure 16: Edge AI Processing Cycle

3.4. Cyber-Physical Systems (CPS)

Cyber-physical systems (CPS) are engineered systems built and dependent upon the integration of computational algorithms and physical components. Together with the internet, data, and services available online, embedded systems join to form cyber-physical systems. CPS are enabling technologies that will transform the way people interact with engineered systems. New smart CPS will bring virtual and physical worlds together and enable a networked world where intelligent objects communicate and interact. These technologies promise to revolutionize human interactions with the physical world in much the same way that the internet has transformed human interaction with information. CPS enable interactions between high performance software-based embedded systems and dedicated user interfaces integrated into digital networks. This creates a completely new world of system functionality. CPS use shared knowledge and information from processes to independently control logistics and production systems. They are the bridge that connects IoT with higher-level services, known as the Internet of Services (IoS). Software providers, service providers, brokers and users collaborate to develop flexible applications that can be dynamically integrated with one another. CPS also represent a paradigm break from existing business and market models, as revolutionary new applications, service providers, and value chains become possible. Industry sectors such as the automotive industry, energy, economy and healthcare, will in turn be transformed by these new value chain models. In the future, advances in CPS will enhance human security, efficiency, comfort and health. It is expected that CPS will play a central part in addressing the fundamental challenges posed by demographic change, scarcity of natural resources, sustainable mobility, and energy change. The new generations of CPS and their emerging platforms, such as the IoT and the Industrial Internet of Things (or Industrial Internet) will influence the formation of future smart and connected environments, including smart cities. This will cut across several challenges that will need to be addressed through the creation of a sustainable Industry 4.0 governance model: ensuring control, dependability, networking, privacy, security, safety, transparency and interpretability.

3.5. Blockchain

As per ITU Recommendation ITU-T X.1400, blockchain is a type of distributed ledger which is composed of digitally recorded data arranged as a successively growing chain of blocks with each block cryptographically linked and hardened against tampering and revision.

Unlike traditional centralized systems, blockchain operates on a peer-to-peer network where all participants hold a copy of the ledger. Each transaction is validated through consensus mechanisms such as Proof of Work or Proof of Stake, ensuring trust without the need for intermediaries. Transactions are grouped into blocks, each containing data, a timestamp, and a cryptographic hash of the previous block. This design ensures the integrity and immutability of data, making it nearly impossible to alter records without consensus. Blockchain's key features, such as transparency, traceability, and security, make it suitable for diverse applications across industries, enhancing efficiency and reducing fraud.

Blockchain in Industry 4.0

In Industry 4.0, blockchain plays a crucial role in transforming manufacturing and industrial processes by enabling trust, transparency, and efficiency. It enhances supply chain management by providing end-to-end traceability of goods, allowing stakeholders to verify product origins, transit history, and authenticity. Smart contracts automate transactions and workflows, reducing human intervention, delays, and errors in manufacturing and logistics. Blockchain also addresses security concerns in IoT ecosystems by ensuring the integrity and authenticity of data shared among connected devices. This prevents tampering, unauthorized access, or data breaches. Additionally, it enables secure, real-time sharing of machine performance data across stakeholders, facilitating predictive maintenance and operational optimization in smart factories. By integrating blockchain, Industry 4.0 achieves higher levels of automation, reliability, and collaboration, driving innovation and sustainable growth.

3.6. Big Data

Big data analytics encompasses the techniques, tools, and applications employed to gather, process, and extract insights from diverse, large-scale, and fast-moving data sets. These data sets can originate from various sources, including the web, mobile devices, email, social media, and connected smart devices. They typically involve rapidly generated data in multiple formats, such as structured (like database tables and Excel sheets), semi-structured (like XML files and web pages), and unstructured (such as images and audio files).

ITU, in their recommendation ITU-T Y.2244, has defined Big Data Analytics as the "Scrutiny performed on massive volume of data with the purpose of obtaining meaningful results, such as trends or preferences."

With the analysis of big data, analysts, researchers, and business users are enabled to make better and faster decisions by using previously unused data. For this purpose, advanced analytical techniques such as text analytics, machine learning, predictive analytics, data mining, statistics, and natural language processing can be used. Figure 17 below shows the architecture of Big Data.

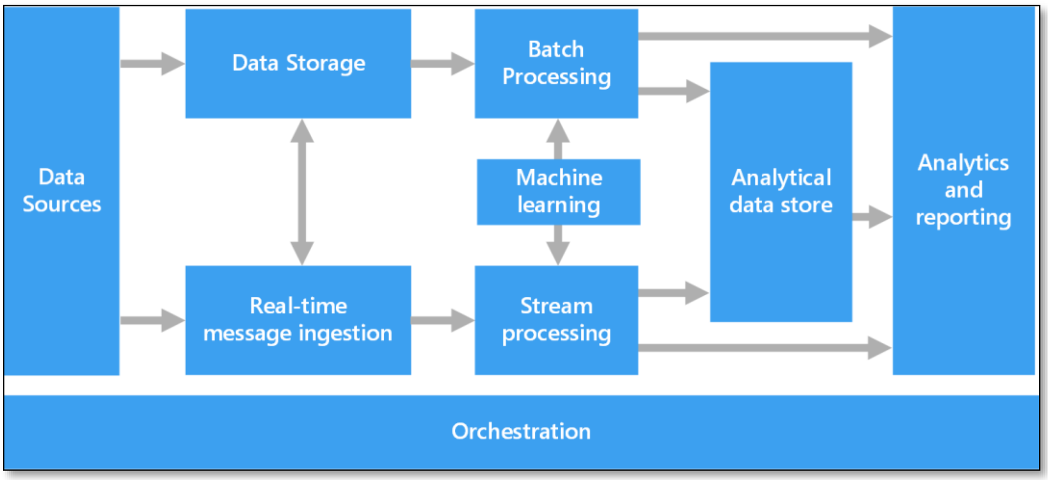

Figure 17: Big Data Architecture

[Source: Microsoft Azure][17]

The use of analytics based on extensive data sets has recently gained traction in the manufacturing sector, significantly enhancing production quality, reducing energy consumption, and improving equipment maintenance. In the realm of Industry 4.0, the standard practice will involve collecting and thoroughly evaluating data from diverse sources—ranging from production equipment and systems to enterprise and customer management systems—to facilitate real-time decision-making.

For example, semiconductor giant Infineon Technologies has managed to reduce product failures by linking single-chip data captured during the final testing phase with process data collected earlier in the wafer status phase. This approach allows Infineon to detect patterns and identify defective chips early in the production process, thereby enhancing overall production quality.

Moreover, the integration of advanced analytics in Industry 4.0 will enable predictive maintenance, minimizing downtime and extending the lifespan of machinery. Real-time data analysis will also support adaptive manufacturing processes, allowing for dynamic adjustments based on current conditions and demand. This not only improves efficiency but also fosters innovation through the continuous optimization of production methods. Additionally, the seamless flow of information across the supply chain will enhance collaboration and transparency, leading to more agile and responsive manufacturing ecosystems.

Unified Namespace (UNS)

The Unified Namespace, or UNS in short, is like a common language or backbone that helps connect all the different systems and departments in an organization—from the shop floor to the top floor. Instead of having scattered data in different software or machines, UNS brings everything together in one place in real time.

[17] https://learn.microsoft.com/en-us/azure/architecture/databases/guide/big-data-architectures

UNS helps in making the data as one source of truth. It organizes the information in a structured way—starting from the company level, moving down to the plant, area, specific line, and even individual machines or equipment. This makes it easy for everyone—from engineers and IT teams to management—to access the same updated information, whenever they need it.

In most cases, MQTT (a lightweight messaging protocol) is used with formats like Sparkplug or JSON to build this system. The best part is, it supports live monitoring and smooth communication between machines, apps, and users, all while keeping things scalable and future-ready.

Whether you're running a single factory or multiple plants across locations, a Unified Namespace helps make digital transformation smoother, more efficient, and well-connected.

3.7. Autonomous Robots

Autonomous robots in Industry 4.0 refer to robots that can perform tasks independently without human intervention, utilizing advanced technologies like artificial intelligence (AI), machine learning (ML), computer vision, and the Internet of Things (IoT). These robots are designed to operate in complex and dynamic environments, making real-time decisions and adapting to changing conditions on the fly.

Manufacturers across various industries have traditionally employed robots to handle complex tasks, but the capabilities of these machines are rapidly advancing. Modern robots are becoming more autonomous, adaptable, and cooperative. In the future, they will be able to interact with each other, work safely alongside humans, and even learn from human actions. These new-generation robots will be more cost-effective and versatile compared to the current models used in manufacturing.

For instance, Kuka, a prominent European manufacturer of robotic equipment, provides autonomous robots that can interact and collaborate with one another. These interconnected robots can coordinate their actions to adapt to the next unfinished product in the assembly line automatically. Equipped with high-end sensors and advanced control units, they facilitate close collaboration with human workers. Similarly, ABB, a leading supplier of industrial robots, has introduced YuMi, a two-armed robot designed to assemble products like consumer electronics alongside humans. YuMi's padded arms and computer vision capabilities ensure safe human-robot interaction and accurate parts recognition. One of the other pioneers in this field is Mobile Industrial Robots (MiR), shown in figure 18 below:

Figure 18: Mobile industrial Robot (MiR)

[Source: International federation of Robotics][18]

Applications of autonomous robots in Industry 4.0:

1. **Manufacturing and Assembly:** Autonomous robots can handle complex assembly tasks, working alongside humans (cobots) or entirely on their own. They can switch between different tasks, improve precision, and enhance production efficiency.
2. **Logistics and Supply Chain:** In warehouses and distribution centers, autonomous robots manage inventory, pick and place items, and transport goods. They optimize logistics by reducing time and errors associated with manual handling.
3. **Quality Control:** These robots are equipped with sensors and AI to inspect products in real-time, ensuring high standards of quality and detecting defects early in the production process.
4. **Maintenance:** Autonomous robots can perform predictive maintenance tasks, identifying and fixing issues before they lead to equipment failures. This reduces downtime and extends the life of machinery.
5. **Agriculture:** In smart farming, autonomous robots plant, monitor, and harvest crops. They use data from sensors and drones to make decisions that optimize yield and resource use.
6. **Healthcare:** Autonomous robots in healthcare settings assist in surgeries, deliver supplies, and support patient care, improving the efficiency and safety of medical procedures.

The advancements in autonomous, flexible, and cooperative robots are transforming manufacturing, leading to safer, more efficient, and adaptable production systems. As these robots continue to evolve, they will play a pivotal role in the realization of Industry 4.0, driving forward the next wave of industrial innovation.

[18] https://ifr.org/news/the-autonomous-way-to-industry-4.0/

3.8. Augmented Reality (AR) and Virtual Reality (VR)

Augmented reality (AR) systems are beginning to revolutionize various industrial services, such as part selection in warehouses and delivering repair instructions via mobile devices. Although these systems are still in the early stages of development, their future applications are poised to significantly expand, offering workers real-time information that enhances decision-making and work processes.

For instance, technicians might receive step-by-step repair instructions through AR glasses as they inspect the equipment that needs servicing. This real-time guidance displayed directly in their field of vision can streamline the repair process and reduce errors.

Another promising application of Augmented reality (AR) is in virtual training environments. Siemens, for example, has created a virtual plant-operator training module for its Comos software. This module uses a realistic, data-driven 3D environment and AR glasses to train personnel in handling emergencies. In this virtual setup, operators can interact with digital representations of machines, adjust parameters, and access operational data and maintenance instructions, offering a safe and effective training experience.

As AR technology advances, its integration with other Industry 4.0 technologies, such as IoT and AI, will further enhance its capabilities. For example, AI algorithms can analyze data from IoT sensors and provide predictive maintenance alerts through AR, enabling proactive maintenance and reducing unexpected equipment failures. Integration of AR in Industry 4.0 can be seen in figure 19 below:

Figure 19: AR in Smart Manufacturing

[Source: ISA][19]

[19] https://blog.isa.org/augmented-reality-in-smart-manufacturing

3.9. Additive Manufacturing

Additive Manufacturing (AM), commonly known as 3D printing, is a process of creating three-dimensional objects by layering materials based on a digital design. Unlike traditional subtractive manufacturing methods, which involve cutting or removing material from a larger block, additive manufacturing builds objects layer by layer, offering greater design flexibility and material efficiency.

The process begins with a digital 3D model, usually created using Computer-Aided Design (CAD) software, which is then converted into a format readable by a 3D printer. Materials such as plastics, metals, ceramics, or composites are selectively deposited or fused layer by layer using techniques like Stereolithography (SLA), Fused Deposition Modeling (FDM), or Selective Laser Sintering (SLS).

Additive manufacturing is widely used in industries such as aerospace, automotive, healthcare, and consumer goods for prototyping, customized production, and creating complex designs that are challenging or impossible with conventional methods.

3.10. Digital Twin

A digital twin, which is a virtual representation of a physical procedure or product, can significantly enhance efficiency and reduce costs in manufacturing processes. By leveraging digital twins, production teams can analyze various data sources to minimize defective items, improve production efficiency, and reduce industrial downtime.

Digital Twin can visualize assets, track changes, and optimize performance throughout the product lifecycle. The data collected from the digital twin offers a comprehensive view of the lifecycle of products and processes, optimizing workflows in part production, managing supply chains, and ensuring product quality.

In smart manufacturing, digital twins can shorten time-to-market by allowing the design and evaluation of manufacturing processes in virtual environments before actual production begins. They provide comprehensive simulation platforms for simulating and assessing product performance, enabling analysis and modification of produced parts.

Figure 20 below illustrates the design of a Digital Twin for manufacturing, showing the interaction between physical and digital systems through data mapping and feedback.

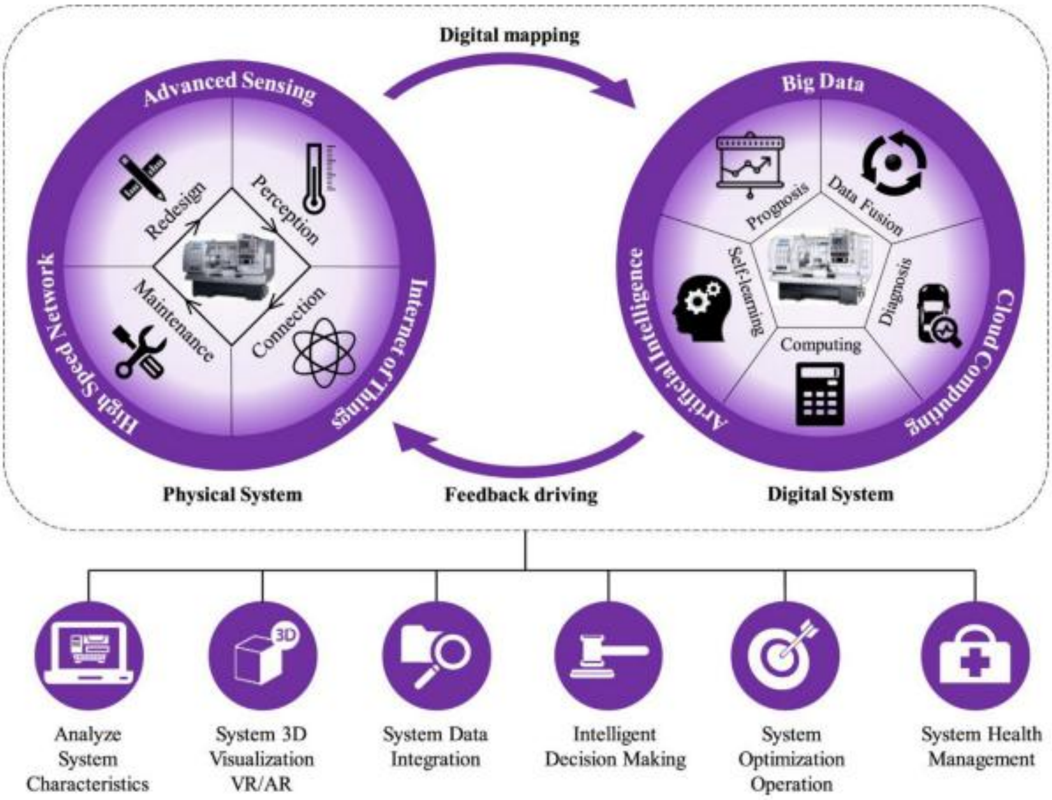

Figure 20: The design of the digital twin for manufacturing

[Source: ResearchGate][20]

Additionally, the commissioning time of a factory can be significantly reduced by using digital twins to develop and optimize factory layouts. The productivity of part manufacturing can also be enhanced through predictive maintenance and data-driven root-cause analysis during the production process.

3.11. Cybersecurity

As per ITU Recommendation ITU-T X.1205, Cybersecurity is the collection of tools, policies, security concepts, security safeguards, guidelines, risk management approaches, actions, training, best practices, assurance and technologies that can be used to protect the cyber environment and organization and user's assets. Organization and user's assets include connected computing devices, personnel, infrastructure, applications, services, telecommunications systems, and the totality of transmitted and/or stored information in the cyber environment. Cybersecurity strives to ensure the attainment and maintenance of the security properties of the organization and user's assets against relevant security risks in the cyber environment. The general security objectives comprise the following:

- Availability

[20] https://www.researchgate.net/publication/371722718_Digital_Twin_for_Smart_Manufacturing_A_Review

- Integrity, which may include authenticity and non-repudiation
- Confidentiality

The integration of advanced connectivity in Industry 4.0 not only improves operational efficiency but also exposes industrial systems to potential cyber vulnerabilities. As more devices and systems become interconnected, the attack surface for cyber threats expands, making robust cybersecurity measures imperative.

One key aspect of enhancing cybersecurity in this new era involves the deployment of secure communication channels that prevent unauthorized access and data breaches. This includes the use of encryption protocols to protect data in transit and at rest, ensuring that sensitive information remains confidential and tamper-proof.

Moreover, identity and access management (IAM) systems are essential for controlling and monitoring who or what can access specific parts of the production network. Implementing multi-factor authentication (MFA), role-based access control (RBAC), and regular audits of access logs are critical steps in securing these systems.

The partnerships between industrial-equipment vendors and cybersecurity21 companies signify a strategic move to integrate specialized security expertise with industrial operations. These collaborations aim to develop comprehensive security solutions tailored to the unique needs of industrial environments. For example, integrating AI and machine learning into cybersecurity frameworks can enhance threat detection and response times, providing real-time protection against sophisticated cyber-attacks.

Additionally, these collaborations help in establishing industry-wide standards and best practices for cybersecurity in manufacturing. By creating a unified approach to security, companies can ensure a higher level of protection across the entire supply chain, from raw materials to finished products.

In summary, the transition to Industry 4.0 necessitates a strong focus on cybersecurity to protect increasingly interconnected industrial systems. Secure communications, advanced identity and access management, and strategic partnerships between industrial and cybersecurity firms are critical components in safeguarding against emerging threats and ensuring the reliable and safe operation of manufacturing processes.

[21] https://www.nist.gov/blogs/manufacturing-innovation-blog/cybersecurity-and-industry-40-what-you-need-know

4. Advantages of Adopting Industry 4.0

The adoption of Industry 4.0 technologies represents a paradigm shift in manufacturing and industrial processes, bringing unprecedented levels of automation, connectivity, and data-driven insights. According to the International Telecommunication Union (ITU), Industry 4.0 is built on the integration of advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), big data analytics, cloud computing, and automation systems. These technologies empower manufacturers to create "smart factories" where machines, sensors, and systems communicate and make decisions autonomously. This transformation leads to enhanced operational efficiency, greater flexibility in production, and improved quality control. Industry 4.0 also opens up opportunities for manufacturers to respond more rapidly to changing market conditions, enabling them to create highly customized products tailored to specific customer needs without significant cost increases. By embracing these technologies, industries can foster continuous innovation, improve safety standards, and reduce operational costs while simultaneously promoting sustainability. These advancements are key to improving competitiveness in an increasingly digital and interconnected global market.

Some of the important advantages of adopting Industry 4.0 are as follows:

1. **Enhanced Operational Efficiency**: Industry 4.0 technologies enable real-time monitoring and optimization of production systems. Automation and data exchange between machines and systems reduce the need for manual interventions, streamlining workflows and improving operational efficiency.

2. **Increased Flexibility and Customization**: The ability to quickly adapt production lines to meet specific customer demands is a major benefit of Industry 4.0. Manufacturers can easily implement mass customization without incurring significant costs, allowing for personalized products on demand.

3. **Predictive Maintenance and Reduced Downtime**: By utilizing IoT sensors and AI algorithms, companies can predict equipment failures before they occur, thereby minimizing unplanned downtime. This proactive approach reduces maintenance costs and extends the lifespan of machinery.

4. **Data-Driven Decision Making**: With access to large volumes of real-time data, manufacturers can make informed decisions quickly. The ability to process and analyze data allows companies to optimize supply chains, improve quality control, and respond promptly to market changes.

5. **Improved Safety**: Industry 4.0 improves worker safety through enhanced human-robot collaboration and automation of hazardous tasks. Real-time monitoring and smart systems can detect risks and prevent accidents, ensuring safer working conditions.

6. **Sustainability and Resource Efficiency**: The optimization of resources such as energy, materials, and human labour plays a crucial role in achieving sustainability goals. Industry 4.0 solutions help companies reduce waste, enhance energy efficiency, and implement greener manufacturing practices.

7. **Global Competitiveness and Innovation**: As Industry 4.0 technologies are standardized globally, they create new opportunities for businesses to innovate, expand into new markets, and maintain a competitive edge. Standardization also enables interoperability, fostering collaboration across industries and regions.

Figure 21 below depicts "Digital Compass" which maps various Industry 4.0 levers to specific value drivers such as quality, time to market and asset utilization, helping companies identify the right tools to meet their business goals.

Figure 21: Industry 4.0 Opportunities

[Source: McKinsey&Company][22]

[22] https://www.mckinsey.com/capabilities/operations/our-insights/manufacturings-next-act

5. Challenges of Industry 4.0

5.1. Technical Challenges

i. **Interoperability:** In Industry 4.0, different machines, systems, and devices often use proprietary protocols and standards, making it difficult for them to communicate and work together seamlessly**.**

ii. **Connectivity:** In semi-urban and remote areas, particularly for MSMEs, typical connectivity challenges, includes Limited Access to High-Speed Internet, High Cost of Enterprise-Grade Connectivity, Inadequate Network Redundancy, Lack of Technical Expertise, Limited Support for Emerging Technologies, Fragmented and Legacy IT Infrastructure, etc.

iii. **Controller Integration:** Typical Controller Integration challenges in general and MSMEs in specific, includes Legacy and incompatible PLCs / CNCs, Lack of standardization across control systems, limited skilled workforce for integration, High cost of controller upgrades and system downtime, Poor security practices during controller-network integration, Controllers not designed for smart data exchange, etc.

iv. **Sensor Integration:** Typical Sensor Integration challenges in general and MSMEs in specific, includes high cost of industrial-grade and smart sensors, difficult retrofitting on legacy machines, diverse sensor protocols and integration hurdles, Limited expertise in setup, calibration, and data analysis, new cybersecurity concerns with smart sensors, etc.

v. **Cyber Security:** With increased connectivity comes greater risk of cyberattacks. IoT devices, cloud computing, and data exchange between machines create potential vulnerabilities.

vi. **Data Integration and Management:** Industry 4.0 generates vast amounts of data. Integrating data from multiple sources (machines, sensors, supply chain) and making it actionable is a major challenge.

vii. **Latency and Bandwidth Issues:** In Industry 4.0 environments, vast amounts of data are generated by IoT devices, sensors, and machines. Processing this data in real time is crucial for tasks like predictive maintenance, quality control, and operational efficiency. However, ensuring low latency and sufficient bandwidth for data transmission, especially in complex industrial settings, can be challenging. This is particularly problematic in remote locations.

5.2. Organizational Challenges

i. **Resistance to Change:** Cultural resistance within organizations can hinder the adoption of Industry 4.0. Employees may fear automation, worry about job security, or be reluctant to change familiar processes.

ii. **Legacy Systems and Infrastructure:** Many manufacturers rely on outdated, siloed systems that aren't compatible with modern Industry 4.0 technologies. Upgrading or replacing legacy systems is often costly and complex.

iii. **High Initial Investment:** Implementing Industry 4.0 technologies often requires substantial upfront costs for equipment, software, and training. Many companies struggle with the capital requirements.

iv. **Lack of Technical Skills:** Industry 4.0 demands new skill sets in data analytics, IoT systems, machine learning and automation. Many existing workforces aren't prepared for the technological shift.

5.3. Regulatory and Standardization Challenges

i. **Regulatory Compliance:** The rapid pace of technological change in Industry 4.0 can outstrip the ability of regulatory bodies to keep up. Companies may face uncertainty about how new technologies will be regulated, especially in areas such as data protection, cybersecurity, and product safety. Navigating these evolving regulatory landscapes can be challenging.
ii. **Lack of Standards based deployments:** Industry 4.0 involves integrating various technologies from different vendors, but the lack of standards based deployments leads to issues related to inter connectivity, data sharing and interoperability.
iii. **Proper Electronic Waste Management:** Ensuring environmentally sound management of electronic waste remains a regulatory challenge. This includes promoting safe disposal, recycling and reuse to mitigate ecological harm. Key concerns involve lack of awareness, inconsistent enforcement of e-waste regulations and inadequate implementation, which hinder sustainable waste management.
iv. **Data-Driven Policy Management:** The formulation and enforcement of data-driven policies face challenges related to data security, privacy and standardization. Absence of harmonized governance frameworks, varying levels of compliance with data protection regulations and evolving cyber threats make it difficult to implement consistent risk assessment and encryption standards. These gaps impact trust, interoperability and the effective use of data in policymaking.

5.4. Challenges for conversion to smart factories

The conversion from traditional industries to smart industries through the adoption of Industry 4.0 technologies is a complex and multi-faceted process that comes with several challenges. Industry 4.0 involves the integration of advanced technologies such as automation, artificial intelligence (AI), the Internet of Things (IoT) and data analytics into existing manufacturing and industrial processes. Industry 4.0 further requires accurate and real-time data from the field operations in the factory. For this purpose, it is mandatory to have seamless integration of OT (Operation Technology) and IT (Information Technology). With huge capital expenditure over the years, the machines in traditional factory would be working on various automation levels i.e. they may be at Industry 3.0 level (with PLC and instrumentation) or even at Industry 2.0. Unfortunately, most of the instruments in the existing machines do not support integration with IIoT. This makes OT-IT integration as one of the major challenge in traditional factories. Other challenges ranging from technological to organizational, regulatory, and financial issues that require careful consideration and strategic planning have been described below:

1. **Integration of Legacy Systems with Modern Technologies**: One of the foremost challenges in the transition to smart industries under Industry 4.0 is the integration of legacy systems with modern IT and digital technologies. Many traditional industries continue to rely on older machines and equipment that were not originally designed for connectivity or digitalization.

Retrofitting these machines for data acquisition is feasible but often demands significant investment, technical expertise and customized solutions. A key aspect of this integration involves understanding and capturing data from existing machinery. This begins with identifying the available OT protocols in the system such as RS232, RS485/Modbus, TCP/IP and analog inputs and selecting critical parameters required for IIoT and AI-based processing. These parameters must then be translated into usable data points for the IT platform through the use of connectors or gateways. In cases where existing systems lack necessary instrumentation, new hardware components, sensors or jigs/fixtures may need to be added to facilitate data capture. A viable approach to address these challenges is the development and deployment of standardized, interoperable data collection systems that can bridge the gap between legacy and modern equipment, enabling effective real-time monitoring, decision-making, and process optimization.

2. **Data Standardization and Interoperability**: Data standardization is another critical barrier. The data generated by machines, sensors and systems in a smart factory must be uniform in format and easily interpretable across different devices and platforms. Data standardization should cover various aspects of production, maintenance, quality control, process parameters and environmental factors. Without standardized data formats, the smooth integration of new systems and the effective analysis of data are hindered, leading to inefficiencies. Additionally, interoperability between different systems and vendors remains a significant concern. It is crucial to develop open data acquisition protocols and ensure that systems can communicate seamlessly.

3. **Cybersecurity and Privacy Concerns**: As industries move towards smart factories, the volume of data generated and shared increases exponentially. This influx of data can become a potential target for cyberattacks, raising concerns about cybersecurity and data privacy. The importance of implementing robust cybersecurity measures to protect sensitive industrial data. With the interconnectedness of machines, sensors, and cloud-based systems, the vulnerability to cyber threats also grows, making it critical for organizations to prioritize cybersecurity during their digital transformation.

4. **Skilled Workforce and Talent Gap**: Another significant challenge is the shortage of skilled workers who are equipped with the knowledge and expertise to operate and maintain Industry 4.0 technologies. The shift to smart industries demands workers who are proficient in areas such as data analytics, AI, machine learning, and cybersecurity. According to the ITU, addressing the skills gap through training, upskilling, and educational initiatives is essential for the successful adoption of Industry 4.0. The transition to smart industries requires not only the technology but also a workforce capable of managing and optimizing these advanced systems.

5. **High Initial Investment and ROI Concerns**: The financial burden associated with the implementation of Industry 4.0 technologies is another obstacle. The high upfront costs of upgrading legacy systems, implementing automation, and setting up the necessary infrastructure can deter traditional industries from adopting Industry 4.0. While the potential for cost savings, increased productivity, and operational efficiencies in the long term is significant, the ITU highlights that industries may struggle with justifying the return on investment (ROI) in the early stages of adoption. A well-defined strategy that clearly outlines

the benefits of Industry 4.0 and its long-term impact on competitiveness can help mitigate this concern.

6. **Regulatory and Standards Compliance**: As industries evolve, the regulatory frameworks that govern them must also be evolved at the same pace. There is a need for clear and comprehensive regulations that guide the adoption of Industry 4.0 technologies. Ensuring that the transition complies with safety standards, environmental regulations, and data protection laws is essential. However, many countries and regions still lack unified standards, which can create challenges for organizations operating across multiple jurisdictions. The development of global standards for Industry 4.0 applications, such as data security protocols and interoperability guidelines, is critical for fostering innovation while ensuring compliance.

7. **Data Management and Governance**: As industries become more data-driven, managing and governing the vast amounts of data generated becomes increasingly important. The ITU stresses the need for robust data management strategies to ensure that data is accurate, accessible, and secure. This requires implementing clear data governance policies, particularly in areas such as data ownership, data sharing, and data privacy. With the right data management practices in place, organizations can unlock the full potential of Industry 4.0 technologies and ensure that their data assets are effectively utilized.

5.5. Challenges faced by Manufacturing MSMEs

Manufacturing MSMEs face numerous challenges related to infrastructure, operations and digitization. Some of the key challenges are listed below:

- Lack of knowledge on how to develop and implement engineering solutions to digitize manufacturing facilities effectively
- High capital investment required to setup and maintain digital infrastructure
- Unavailability of skilled workers and partners to implement and maintain such digital systems
- Unwanted downtimes and breakdowns
- Low productivity and efficiency of the plant
- Product quality issues and associated reworks
- Increasing operational costs i.e., high power consumption, material wastage, maintenance cost, excessive inventory etc.
- Limited reach to customers, especially in international markets
- Lack of compliance to worker safety regulations in plants
- Difficulty in analyzing operational data and translating insights into measurable financial or economic benefits.

5.6. Challenges in scaling up the MSME digitalization

There are multiple challenges in scaling up the MSME digitalization to the national level. Some of the key challenges are listed below:

- **Outreach** – Considering the low awareness of MSMEs about smart manufacturing, it is necessary to address large number of MSMEs and make them aware about Industry 4.0 and digitalization. To bring more manufacturing MSMEs into the workshops, support from other stakeholders of the ecosystem such as Industry association and government is needed.
- **Budget of SMEs** – While large companies have started investing in Technology, Small and Medium enterprises still face constraints in allocation of budget to technology spending.
- **Lack of confidence in technology** – The MSME business owners face challenge in starting the digital journey due to inexperience of returns obtained through deployment of solutions in the plants. There is a need for an initial push which can help them to start the digital journey at the critical areas and later drive digitalization on their own in the entire plant.

6. Overcoming challenges through digital adoption

In the current scenario, many MSMEs have high end automation and machines in place and few of them even have adopted Enterprise Resource Planning (ERP) solutions. However, the data lies idle in the system which has potential to provide several insights for better decision making. The Future systems will need to be integrated where man and machine talk to each other through data and for this to happen, Digitalization is required.

There are multiple low cost and easy to deploy Industry 4.0 solutions, which are made using advanced technologies and can solve operational challenges of manufacturing enterprises. For example, the digital solutions for Paperless operations can digitize the data recording and generate insights from analytics to improve operations and optimize processes. Condition Monitoring of critical equipment prevents them from unwanted breakdown. Computer vision-based inspection of products can highlight quality defects. Augmented Reality based Virtual Plant Visits can drive customer and partner engagements, in addition AR/VR solutions can also help on remote collaborations and workforce training. Smart warehousing and supply chain solutions provides material monitoring, theft security and storage & movement tracking solutions. Figure 22 below highlights Industry 4.0 use cases, solution and business benefits:

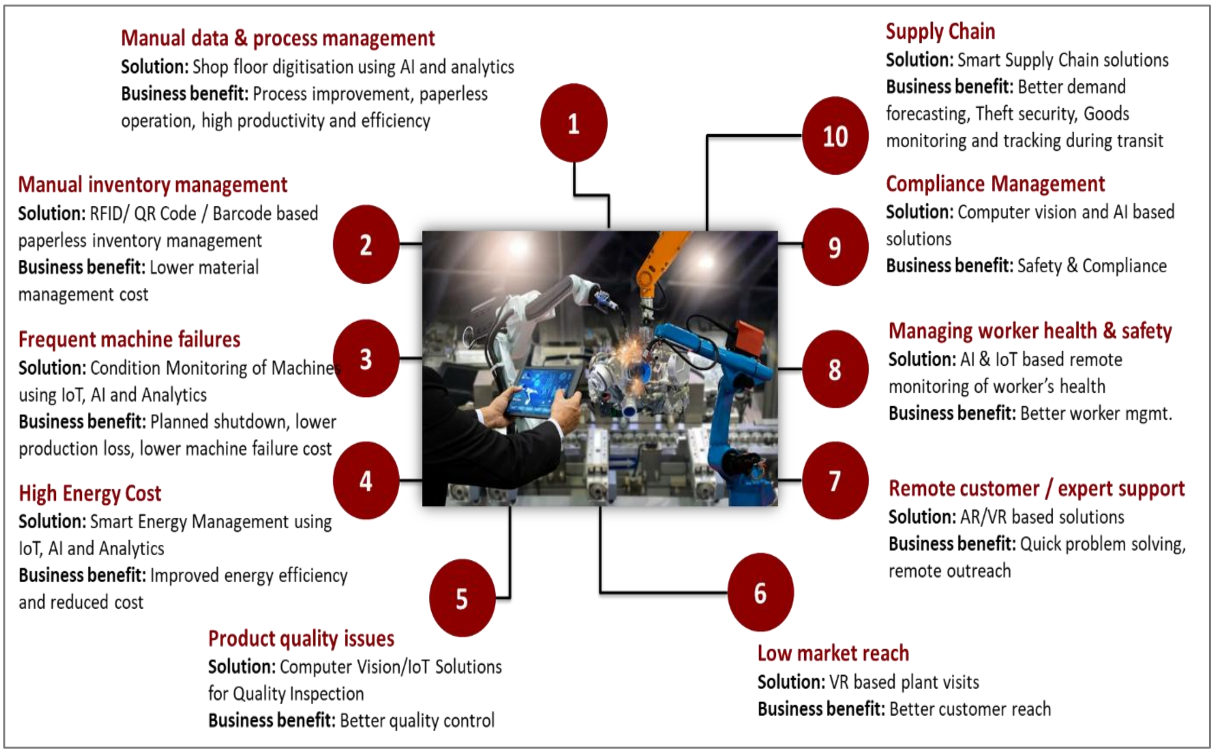

Figure 22: Industry 4.0 use cases

6.1. Digital adoption among MSMEs

In the era of Fourth Industrial Revolution (Industry 4.0), the gap between the virtual and real world is reducing in an unprecedented manner resulting in ease of operations but at the same time demanding higher efficiency and flexibility in our plants. In the current scenario, where Innovation is the priority for the enterprises, technology has become a key driver for the manufacturing transformation.

It has become imperative for enterprises to build digital capabilities in advanced technologies such as Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), Augmented Reality (AR) etc. to stay competitive globally. Digitalization has potential to transform supply chain, boost productivity and improve manufacturing efficiency. If adopted with the right approach, it can pave the path of digital led growth of the enterprise.

Digitalization refers to the use of advanced technologies such as AI, IoT, ML, AR etc. to collect and analyze vast amounts of data in real-time, enabling enterprises to make better informed decisions and improve their operations. For Manufacturing Enterprises, digitalization helps to reduce operational cost and improve growth, productivity and efficiency in plants. The process of digitalization can be visualized as a step by step process as depicted in figure 23 below:

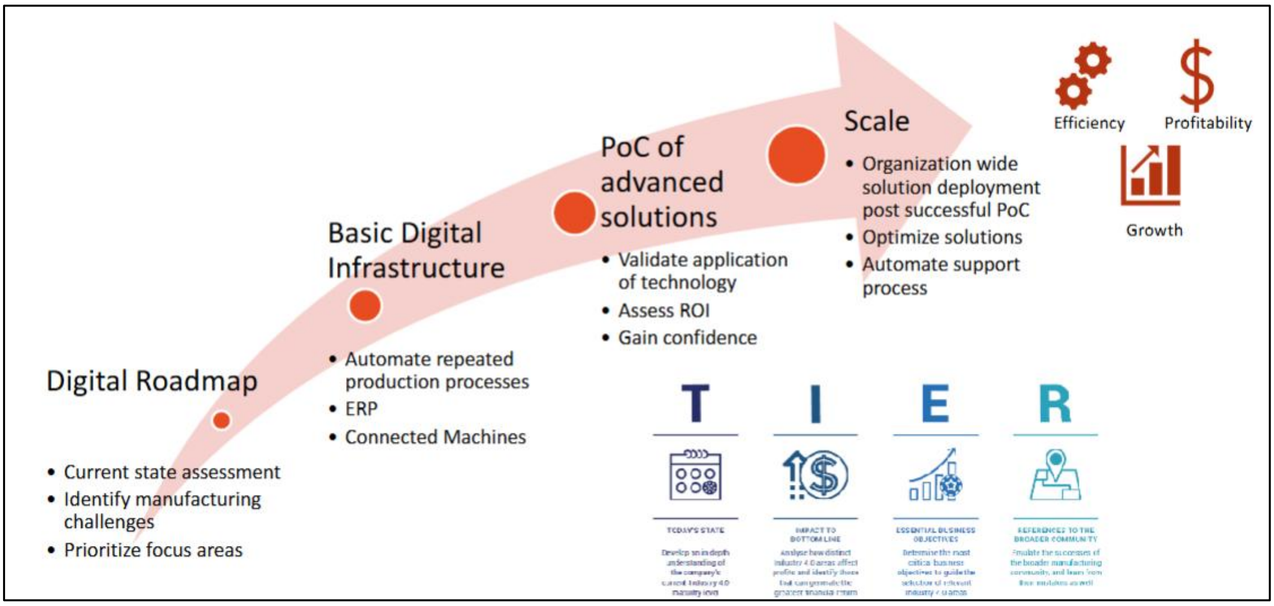

Figure 23: Step by step approach for Digitalization

[Source: Nasscom CoE for IoT & AI]

6.2. Barriers of Digital Adoption

MSMEs face **4As** - **A**wareness, **A**vailability of skilled resources, **A**ccessibility and **A**ffordability related challenges in implementing digitalization in the enterprise.

Very few MSMEs have implemented solutions or have realized the benefits. This calls for an action to make manufacturing enterprises aware about Industry 4.0, which can help to address the manufacturing challenges and generate the value by improving performance of the plant.

Second challenge is availability of skilled resources. MSMEs have workforce which lack digital literacy, making it difficult to transition to more advanced digital tools and solutions. The need is to build capabilities to see the applications of tech solutions in the real-world scenario and utilize them after implementation to take the informed business decisions.

Third challenge is accessibility. MSMEs do not have access to the pool of solution providers who can provide digital solutions. Even if they connect with few, it becomes challenging for them to evaluate the technical proposals provided by the solution providers.

Fourth challenge is affordability. MSME enterprises have limited budgets to spend on technology. Consultations suggest that it is not feasible for MSME manufacturing companies to work with the large tech companies due to budget constraints. MSMEs are unable to justify the return on investment due to high tech spending cost.

The Micro manufacturing enterprise may not adopt the technology due to the micro scale of the operations, but they can start building capabilities to understand the digitalization process, so that they become future ready with the growth of the organization.

While large companies are steadily progressing towards digitalization and adopting smart manufacturing solutions, many medium and small enterprises are yet to fully embark on this journey. As a result, the immense potential for innovation and scalability within the Indian MSME sector remains largely untapped, which may impact their overall competitiveness and technological advancement. A significant number of these enterprises face challenges in initiating this transition, often due to a lack of clarity on how and where to begin.

6.3. Role of Start-ups and Tech SMEs in Digital Adoption by MSMEs

Start-ups and Tech SMEs play a very important role in manufacturing transformation of MSMEs by providing low-cost innovative solutions. As per a report by Nasscom[23], the deep tech startup ecosystem in India has reached to around 3600+ startups with more than 60% in AI, followed by Big data and Analytics, IoT, Block Chain, AR/VR etc.

Industry 4.0 solutions are primarily software made using advanced technologies with supporting hardware if required. For example, to prevent machines from unplanned downtimes and failures, the solution continuously monitors critical health parameters of the machine such as noise, vibration, oil level, temperature etc. The modern machines are equipped with Programmable Logical Controllers (PLCs) from where the data can be extracted and monitored continuously. In legacy machines, hardware such as sensors and meters are needed, which are retrofitted on the machines to extract the data. The data is further analyzed to generate insights which can help in better decision making, reduce costs and improve efficiency.

The cost of digital solutions varies based on problem area, scale of implementation, hardware needed and the solution provider. However, these expenses can be recovered from the positive business outcomes generated after the implementation of the solution. For example, stakeholder consultations suggest that Smart Energy Management solutions can reduce energy consumption

[23] India's deep tech dawn – Forging Ahead – Nasscom Zinnov Report – June 2024 https://nasscom.in/knowledge-center/publications/indias-deeptech-dawn-forging-ahead#

by 3-5%. Condition monitoring solution can improve the health of machine by 8-10% and reduce maintenance cost. Camera based quality inspection can reduce the defect rate by 6-8% and reduce the cost of poor quality or wastage. The monetary beneficial impact depends on the magnitude of the problem and unit cost. Hence, reduction in operational cost is one of the decisive factors to prioritize the areas of deployment of the solution.

6.4. Key connectivity solutions

i. Use Industrial-Grade Cables and Connectors
- Ensure Foil Twisted Pair (FTP) or Shielded Foil Twisted Pair (SFTP) cables are used.
- The shielding (foil) is critical—not the category (CAT 6 / CAT 7).
- Use industrial-grade connectors to withstand harsh environments.

ii. Cable Length Limitations
- Maximum cable length: 80 meters.
- For longer distances:
  Use a Network Switch, or Switch to Optical Fiber cables.
- Avoid using couplers or passive I/O modules to extend cable lengths.

iii. Edge Controller Deployment - Install an Edge Controller on-premises to:
- Enable data buffering,
- Minimize latency,
- Ensure reliable data transmission in case of network outages.

iv. Machine Classification for Digital Connectivity - Classify equipment to streamline connectivity strategies:
- Fully Compatible:
  Machines with Ethernet-based communication.
  Direct RJ45 connection possible.
- Semi-Compatible:
  Machines without Ethernet, but with interfaces like RS232, Modbus, DeviceNet, etc.
  Use a Protocol Converter to bridge these to Ethernet.
- Non-Compatible:
  No communication interfaces.

v. Wireless Network Considerations
- Conduct an environmental survey to measure Signal attenuation and Effective range.
- Metal-heavy environments lead to significant wireless signal degradation.
- Exercise caution when deploying wireless.

6.5. Strategies for effective Data Integration

i. Data Storage Infrastructure

- The infrastructure must be scalable, secure and support your data management strategy, considering both performance and cost.
- Opt for cloud storage solutions that offer scalability and flexibility, ensuring your data storage grows with your needs. However, note that the costs for cloud storage could be expensive when used for long periods of time (i.e over 1 year)
- Distributed databases: For high availability and fault tolerance, consider using distributed databases (e.g., NoSQL systems like InfluxDB, Cassandra or MongoDB) depending on the nature of the data.
- Implement data tiering: Store frequently accessed data in faster, but more expensive storage (e.g., SSDs) and less frequently used data in cheaper, slower storage (e.g., hard drives or cold storage).

ii. Sampling Rate

- Adjust the frequency of data collection to the necessary granularity. Avoid excessive data collection to reduce unnecessary processing and storage load.
- Adaptive Sampling: Implement algorithms that adjust the sampling rate dynamically depending on data change rates (e.g., sample every second when significant changes are detected, otherwise reduce frequency).
- Use event-driven data collection (i.e., collect data only when there's a significant value change).
- Apply rate-limiting protocols that only transmit data changes, rather than polling the system continuously.

iii. Data Transfer

- Ensure only essential data is transferred. Prioritize the transmission of data that is crucial for real-time decision-making or performance metrics.
- Implement data compression techniques to reduce the volume of transferred data.
- Use data filtering and aggregation strategies to minimize redundant information.
- Set up data transfer protocols to automatically discard non-critical data or aggregate parameters at the edge before transferring to centralized systems.

iv. Data Retention Period & Redundancy

- Efficiently manage the lifecycle of data, ensuring it is stored for the appropriate duration and is properly backed up for disaster recovery purposes.
- Set up data lifecycle management policies that define when data should be archived, deleted, or moved to lower-cost storage.
- Use automated retention policies to delete or archive data based on the established retention period.
- Implement redundancy through regular backups and replication across multiple geographical locations to safeguard against data loss.

- Disaster Recovery (DR): Create and test DR plans to ensure data recovery mechanisms are robust and quick.

6.6. Government's enabling role in driving Digital Adoption

The support from the government for digitalization can be a great boost in taking the Smart Manufacturing Forum initiative to large number of MSMEs in the country. Below are some of the areas where support from government is needed to scale the program at national level:

- To boost the initiation of digitalization journey, the Industry/ MSME department can provide subsidies for deployment of 1 or 2 digital solutions in the plant, which will help MSMEs to build the initial confidence in digitalization. After seeing the benefits, MSMEs will spend on their own in the technology.
- Special incentives for implementing tech-based solutions which is aimed at reducing carbon emissions & brings sustainability.
- SME Delegations / Exchange program with other technologically advanced countries to understand how SMEs in that countries have adopted advanced technologies in their businesses.
- Digital Experience Zones and Test beds (domain specific i.e. pharma, automotive, agriculture etc.) can be created at multiple locations in India where MSMEs can see the demos of digital solutions and startups/ tech SMEs can test and evaluate their applications before implementation.

6.7. Best Practices and learnings from other countries

The table 2 below shows some of the best practices followed by other countries in driving digital adoption in the industries.

Table 2: Best practices followed by other countries

Incentive for accelerating digital adoption	**Best practices**
Dedicated program / policy for the digital adoption	Various countries implemented dedicated programs or policies to accelerate digital adoption. Some of the examples are Canada digital adoption program, Industry4WRD policy in Malaysia, Digital Europe Program, UAE Industry 4.0 Program
Digital Transformation Accelerator and Network of European Digital Innovation Hubs	Using hub and spoke model, where hub's (digital accelerator) role is to monitor the digital program implementation and guide spokes (innovation hubs)

Incentive for accelerating digital adoption	Best practices
	which will act as multipliers of digital capabilities built under the program.
Digital Readiness Assessment (Malaysia & UAE)	Policy benefits channelized and prioritized to deserving SME candidates who are ready for the digital adoption i.e. have reached a level of growth and operational excellence. The candidates are identified through assessment conducted by the agencies appointed by Government.
Policy benefits (Canada, Malaysia, UAE)	Various benefits provided by the governments. Some of the examples are as follows: • Funding support to adopt the smart solutions (matching grant, interest subsidies) • Skill building assistance (funding for training the workforce to build digital capabilities) • Financing – Loans from public and private banks to finance the digitalization initiatives taken up by the companies. • Other benefits – Tax and custom duty exemptions for procuring hardware or availing tech services

[Source: Official websites of UAE Industry 4.0 Program, The Digital Europe Program, Canada Digital Adoption Program, Industry4WRD Malaysia]

7. Role of 5G in driving Industry 4.0

The transition to Industry 4.0 represents a paradigm shift in how industries operate, driven by the convergence of digital technologies such as automation, data analytics, AI and IoT. This fourth industrial revolution hinges on the seamless integration of cyber-physical systems that link the digital world with the physical world through intelligent devices and real-time data processing. As these technologies continue to evolve, demand for faster, more reliable and more flexible communication networks has never been greater. This is where 5G technology and advanced telecom infrastructure play a pivotal role in enabling and accelerating Industry 4.0.

5G, the fifth generation of mobile communication technology, goes far beyond just providing faster internet speeds. It introduces a host of innovations that offer critical benefits such as ultra-low latency, massive connectivity and vastly improved network efficiency. These capabilities are essential for supporting the highly interconnected, data-driven ecosystems that define Industry 4.0. As industrial processes become increasingly reliant on real-time data, remote control and automated decision-making, existing networks, based on older technologies like 4G and Wi-Fi, are simply not equipped to meet these demands. 5G bridges this gap by providing the necessary infrastructure to enable the ultra-responsive, intelligent systems that Industry 4.0 promises.

With features like network slicing, ultra-reliable low latency communication (uRLLC) and massive machine-type communications (mMTC), 5G unlocks new possibilities for industries across the globe. It ensures seamless communication between millions of devices, supports real-time control of autonomous systems and enables the deployment of mission-critical applications in areas such as manufacturing, healthcare, logistics, and transportation. Additionally, private networks and edge computing facilitated by 5G are allowing businesses to deploy tailored, secure and high-performance networks that are purpose-built for their unique needs.

Below are some of the most important features of 5G that play a critical role in driving Industry 4.0:

7.1. Network Slicing

Network slicing is a crucial feature of 5G, allowing telecom providers to create multiple, customized virtual networks within a single physical network. Each slice can be optimized for specific use cases, offering different levels of speed, latency and bandwidth. For instance, an industrial facility can have a dedicated slice for high-speed, low-latency applications like autonomous vehicles, while another slice can serve IoT sensors or edge computing platforms. This enables businesses to tailor network characteristics according to the requirements of specific Industry 4.0 applications, ensuring optimal performance and minimizing disruptions in critical processes.

7.2. Ultra-Reliable Low Latency Communications (uRLLC)

Ultra-Reliable Low Latency Communications (uRLLC) is one of the standout features of 5G, designed to meet the stringent latency and reliability requirements of mission-critical applications. With uRLLC, 5G networks can offer latencies as low as 1 millisecond, making real-time communication and instant data processing possible. This is particularly important for applications that require high precision, such as remote surgery, factory automation, and autonomous vehicles. uRLLC ensures that data can be transmitted and processed almost instantaneously, enabling seamless operation of autonomous systems and automated workflows, which are central to Industry 4.0.

7.3. Massive Machine Type Communications (mMTC)

Massive Machine Type Communications (mMTC) is a feature of 5G that supports the connection of a massive number of devices (often in the order of millions) within a small geographic area. This capability is essential for the Internet of Things (IoT), where thousands of sensors, actuators, and other connected devices are deployed within smart factories, supply chains and industrial environments. mMTC allows for low-power, long-range communication with devices, ensuring that a large number of IoT sensors can function simultaneously without overloading the network. This feature enables real-time monitoring and control of industrial processes, predictive maintenance and the optimization of resource usage in an Industry 4.0 ecosystem.

7.4. Captive Networks and Private Networks (CNPN)

Captive and private 5G networks are rapidly emerging as foundational pillars of Industry 4.0, offering enterprises the ability to build dedicated, secure and ultra-reliable communication infrastructures tailored to their specific operational needs. Unlike public networks, private 5G networks provide complete control over network architecture, data flow and security protocols, enabling businesses to customize performance, ensure data sovereignty and maintain operational continuity without external dependency. These networks support ultra-low latency and high bandwidth, making them ideal for mission-critical industrial applications such as autonomous robotics, predictive maintenance, real-time monitoring and digital twin implementation. In smart factories, warehouses and remote industrial facilities, private 5G networks act as a digital backbone, facilitating seamless machine-to-machine communication, adaptive production lines and AI-driven decision-making at the edge. By enabling highly secure, resilient and scalable connectivity, private networks empower manufacturers to accelerate digital transformation, reduce downtime and unlock new levels of efficiency and innovation.

Countries like USA, Germany, France, Australia, The Netherlands, United Kingdom, Poland etc. have dedicated Private 5G spectrum, and Enterprises can acquire the spectrum directly from the Government to deploy customized Private 5G infrastructure tailored to their use case needs with comprehensive privacy, security and control.

7.5. Enhanced mobile Broadband (eMBB)

Another critical feature of 5G is its ability to support extremely high data throughput. 5G can deliver data speeds of up to 10 Gbps, enabling industries to transmit large volumes of data quickly and efficiently. High data throughput is essential for applications that involve the exchange of large amounts of data, such as augmented and virtual reality (AR/VR), real-time video surveillance and high-definition remote monitoring. In an industrial context, this feature allows for seamless video feeds, advanced simulations and data-intensive applications, improving operational decision-making and enhancing productivity.

7.6. Edge Computing Integration

5G networks are designed to support edge computing, where data is processed closer to the source of the data, rather than being sent to centralized cloud servers. This reduces latency and allows for faster processing of time-sensitive data. For example, in a factory setting, edge computing enables immediate analysis of data collected from IoT devices and sensors, allowing for real-time adjustments to manufacturing processes, predictive maintenance and improved resource allocation. By integrating edge computing with 5G, businesses can ensure that they are not reliant on distant cloud servers, reducing the risk of network congestion and bottlenecks.

7.7. Enhanced Spectrum Efficiency

5G improves spectrum efficiency, allowing more devices to connect and communicate on the same frequency bands without causing interference. The increased efficiency of 5G networks enables better use of available radio frequencies, especially in high-density environments such as factories, airports and smart cities. This ensures that even in the most densely populated areas, industrial operations can run smoothly without congestion, supporting the large-scale deployment of Industry 4.0 technologies such as IoT sensors, real-time data analytics and connected devices.

7.8. Security

The security features of 5G are enhanced to meet the needs of industries that handle sensitive data. With advanced encryption, secure authentication and end-to-end security protocols, 5G ensures that communication between devices and systems is secure and protected from cyber threats. The security features of 5G are critical in industries such as healthcare, energy and manufacturing, where data integrity and confidentiality are paramount. Private networks, in particular, provide additional layers of security, ensuring that only authorized users and devices can access and communicate over the network.

As 5G sets the stage for Industry 4.0, 6G is poised to take industrial connectivity to new heights. Expected to launch in the 2030s, 6G will offer speeds up to 100 times faster than 5G, with ultra-low latency, integrated sensing and enhanced network intelligence. This will enable breakthrough applications like real-time holography, AI-driven automation and seamless integration of massive IoT ecosystems. 6G will create a more connected, intelligent and immersive industrial environment, laying the groundwork for future Industrial revolution, where advanced technologies and human creativity merge to drive even more sophisticated industrial innovations.

8. Government of India initiatives for growth of Industry 4.0

8.1. SAMARTH Udyog Bharat 4.0

Ministry of Heavy Industries (MHI) under the Scheme for “Enhancement of Competitiveness in the Indian Capital Goods Sector” has set up 4 Smart Advanced Manufacturing and Rapid Transformation Hub (SAMARTH) Centres namely:

i. Centre for Industry 4.0 (C4i4) Lab, Pune;
ii. IITD-AIA Foundation for Smart Manufacturing, IIT Delhi;
iii. I-4.0 India @ IISc, Bengaluru; and
iv. Smart Manufacturing Demo & Development Cell, CMTI, Bengaluru.

Further, 10 cluster Industry 4.0 experience centres have been approved under the Hub and Spoke model to be established across India by Centre for Industry 4.0 (C4i4) Lab, Pune. The key achievements of the SAMARTH Centres are as given below:

i. Development of Industry 4.0 solutions enabled Model Factory by C4i4, Pune and a production based Smart factory by CMTI Bengaluru;
ii. Over 50 use-cases of Industry 4.0 solutions were compiled for implementation support by C4i4, Pune;
iii. Development of Industry 4.0 Maturity & Readiness assessment tool called Industry 4.0 Maturity Model (I4MM) specific for Indian manufacturing companies. Under this program, C4i4 has conducted assessment of several manufacturing industries;
iv. C4i4 Lab, Pune launched ‘Free Online Assessment Tool’ for self-assessment purpose to help the MSMEs to understand their maturity level in their Industry 4.0 journey in order to accelerate the adoption of Industry 4.0;
v. Over 100 Digital Maturity Assessments completed for Auto Companies; 500+ Improvement initiatives identified for industry; 500+ Digital Champions trained on Industry 4.0 by C4i4 Lab, Pune;
vi. 6 Smart Technologies, 5 Smart Tools, 14 solutions developed by I-4.0 India @ IISc, Bengaluru;
vii. CMTI Bengaluru trained about 5000 professionals on Smart Manufacturing & Industry 4.0;
viii. IITD-AIA Foundation for Smart Manufacturing has collaborated with academic institutions to drive innovation in Industry 4.0 technologies tailored for MSMEs.

SAMARTH Centres have been providing assistance to industries including MSMEs to train the workforce and make them aware about Industry 4.0 technologies in the following ways:

i. Organizing Awareness Seminars/ Workshops and knowledge sharing events on Industry 4.0;
ii. Training industries to create awareness about Industry 4.0;
iii. Providing consultancy (in areas such as IOT Hardware, Software development, data analytics) and incubation support to start- ups including MSMEs.

8.2. National Telecom M2M Roadmap and Its Role in Industry 4.0

The National Telecom Machine-to-Machine (M2M) Roadmap, launched by the Department of Telecommunications (DoT), Government of India, is a strategic initiative aimed at enabling the growth of connected devices and intelligent communication systems across industries. As a key enabler of Industry 4.0 and Smart Manufacturing, the roadmap provides a policy and regulatory framework to foster secure, scalable and interoperable M2M communications across the country.

Chapter 5 of the National M2M roadmap has focus on the government initiative of 'Make in India' and gives government approach in going forward with respect to creation of test bed facilities, product certification, Human Resource and Capacity Building, Center of Innovation, Pilots, Entrepreneurs and start-ups. Internet and Broadband growth in India is majorly using imported devices. For IoT (Internet of Things) and M2M, the government of India wishes to have proliferation based on locally manufactured products and services and accordingly trying to put an eco-system in place. Chapter 7 provides the road ahead for the actions to be taken by the government in this regard. Chapter 6 details how M2M can influence various sectors like Smart Cities, Automobile, Energy and utilities, tax compliance through fiscal registers by making POS online, Water Management, Health care, Agriculture, Safety and Surveillance, Supply Chain etc.

M2M communication is central to the Industrial Internet of Things (IIoT) a foundational pillar of Industry 4.0, enabling machines, sensors, systems, and control units on the shop floor to communicate autonomously and make data-driven decisions in real time. The National Telecom M2M Roadmap is a critical enabler for India's Industry 4.0 vision. By providing a standardized, secure and scalable framework for machine communications, it helps manufacturers embrace digital transformation confidently.

8.3. National Digital Communications Policy (NDCP) and Its relevance to Industry 4.0

The National Digital Communications Policy (NDCP) 2018, introduced by the Government of India, provides a strategic framework aimed at transforming the nation into a digitally empowered society and knowledge economy. While its core objectives focus on enhancing connectivity, enabling next-generation technologies, and ensuring data sovereignty, the NDCP also has strong implications for the advancement of Industry 4.0 and Smart Manufacturing.

National Digital Communications Policy, 2018 envisages three Missions:

i. Connect India: Creating Robust Digital Communications Infrastructure. To promote Broadband for All as a tool for socio-economic development, while ensuring service quality and environmental sustainability.
ii. Propel India: Enabling Next Generation Technologies and Services through Investments, Innovation and IPR generation. To harness the power of emerging digital technologies, including 5G, AI, IoT, Cloud and Big Data to enable provision of future ready products and services; and to catalyse the fourth industrial revolution (Industry 4.0) by promoting Investments, Innovation and IPR. One of the goal of this mission is to 'Accelerate transition to Industry 4.0'.
iii. Secure India: Ensuring Sovereignty, Safety and Security of Digital Communications. To secure the interests of citizens and safeguard the digital sovereignty of India with a focus on ensuring individual autonomy and choice, data ownership, privacy and security; while recognizing data as a crucial economic resource.

Impact on Industry 4.0 Implementation

By facilitating next-generation digital infrastructure, the NDCP acts as a critical enabler of Industry 4.0. It provides the necessary policy support for:

- Accelerated digital transformation of manufacturing units
- Development of smart industrial clusters and connected supply chains
- Integration of SMEs into the digital economy through cost-effective connectivity solutions
- Enabling data-driven decision-making through enhanced network reliability and bandwidth

The National Digital Communications Policy serves as a foundational policy instrument that aligns with and accelerates India's Industry 4.0 ambitions. It provides the necessary digital backbone for factories of the future, where cyber-physical systems, advanced connectivity, and real-time data are central to competitiveness and sustainability.

8.4. Captive Networks Private Networks (CNPN Guidelines)

Department of Telecommunications (DoT) issued comprehensive guidelines for Captive Non-Public Network (CNPN) License vide letter no. No. 20-1333/2022-AS-I dated 27th June, 2022, for the establishment of CNPNs. Private Captive Networks can play a key role in automation and industry 4.0 by providing secure, ultra-reliable, low latency and high throughput communication using advanced technologies.

These networks enable enterprises to achieve low-latency, ultra-reliable communication, greater control over network infrastructure, enhanced data security, and seamless integration with Industry 4.0 technologies such as AI, machine learning, cyber-physical systems and digital twins.

Setting up Captive Non-Public Networks:

As per these guidelines Captive Non Public Networks can be set up in following ways:

(1) Telecom Service Providers (TSPs) with Access Service License may provide private networks as a service to an enterprise by using network resources (such as through network slicing) over its PLMN public network.

(2) TSPs with Access Service License may establish isolated Captive Non-Public Network for the enterprises using IMT spectrum acquired by them.

(3) Enterprises setting up Private Captive Networks may obtain the spectrum on lease from TSPs and establish their own isolated network.

(4) Enterprises setting up Private Captive Networks may obtain the spectrum directly from DoT and establish their own isolated network.

9. Standards and Frameworks for Industry 4.0

Several major standards underpin Industry 4.0, ensuring that technologies and processes are interoperable and secure. These include:

1. **ITU-T Y.4228 - Requirements and framework of industrial IoT (IIoT) infrastructure for smart manufacturing**: Recommendation ITU-T Y.4228 provides requirements and reference framework of the industrial Internet of things (IIoT) infrastructure capabilities for smart manufacturing to help service providers implement their system according to the needs of smart manufacturing and merge existing and newly developed IIoT infrastructure, in order to give the stakeholders of smart manufacturing guidance for their applications. Industrial Internet of things (IIoT) infrastructure for smart manufacturing refers to common facilities based on IoT that support smart manufacturing in industries or sectors. It is independent of the products and production process in specific enterprises.
2. **ITU-T Y.4003 - Overview of smart manufacturing in the context of the industrial Internet of things**: This Recommendation provides an overview of smart manufacturing in the context of the Industrial Internet of things (IIoT). The Recommendation introduces at first smart manufacturing and IIoT, including the smart manufacturing capabilities with respect to the Internet of things (IoT) reference model [ITU-T Y.4000]. Then, with respect to smart manufacturing in the context of the IIoT, it identifies fundamental system characteristics and high-level requirements, specifies a reference model and provides some use cases.
3. **ITU-T H.626.7 - Functional architecture for machine vision systems in smart manufacturing**: Recommendation ITU-T H.626.7 specifies the architecture of machine vision systems for supporting the communication between endpoint, application and machine vision systems in smart manufacturing, so as to help end users and providers to specify the machine vision tasks and the solutions, enhance confidence in machine vision ecosystem and open new applications for machine vision systems.
4. **ITU-T F.748.16 - Requirements for applications and services in smart manufacturing based on machine vision**: Recommendation ITU-T F.748.16 presents the overview and requirements for applications and services in smart manufacturing based on machine vision (MV). It describes the basic concept, scenario and ecosystem of machine vision and identifies several typical requirements, such as data acquisition, data pre-processing and data processing. This Recommendation also gives a reference model for MV-based applications and services in smart manufacturing.
5. **IEC 62541 - OPC Unified Architecture (OPC UA)**: It is a platform-independent, machine-to-machine communication protocol designed for industrial automation. It provides a unified communication framework for data acquisition, monitoring, control, and analytics, enabling secure and reliable data exchange between industrial devices from different manufacturers. Widely used for real-time data collection from sensors, system integration, device interoperability and secure data transmission, OPC UA ensures seamless connectivity and interoperability in industrial environments.

Key Components:

i. **Information Model:** Standardized data models (such as devices, variables, and methods) for describing system components.
ii. **OPC-UA Servers and Clients:** Servers provide data, and clients request or interact with this data using secure and platform-agnostic communication.
iii. **Security:** OPC-UA provides a built-in security layer for authentication, authorization, and encryption.

6. **Industry Communication Standards:**

These standards are some of the examples that govern the communication protocols used by modern sensors and controllers to exchange data in industrial environments.

a) **PROFINET (IEC 61158, IEC 61784):**

A widely adopted industrial Ethernet standard that enables high-speed communication between controllers, sensors and actuators. PROFINET supports real-time data transfer, making it ideal for applications requiring fast response times.

b) **I/O-Link (IEC 61131-9):**

A point-to-point communication standard for connecting sensors and actuators to controllers. I/O-Link facilitates bi-directional communication, which allows for sensor configuration and diagnostics, enhancing the ease of integration and management.

c) **EtherCAT (IEC 61158):**

A high-performance, real-time Ethernet-based fieldbus system suitable for applications requiring very low latency and precise synchronization, such as high-speed control and sensor integration in complex systems.

d) **Modbus (RTU, TCP):**

A widely used protocol in industrial automation that facilitates communication between sensors, PLCs and other controllers. While it’s simpler compared to Ethernet-based protocols, it’s often used in legacy systems and low cost applications.

e) **Ethernet/IP (IEEE 802.3, ODVA):**

A communication protocol for industrial automation that uses standard Ethernet hardware and IP protocols for real-time control. Ethernet/IP supports both I/O and explicit messaging, making it versatile for sensor integration

7. **IEC 62443:** This standard pertains to cybersecurity for industrial automation and control systems (IACS). The goal of this specification is to provide a framework that facilitates addressing current and future vulnerabilities in industrial automation and control system and applying necessary mitigations. Developed by the International Electrotechnical Commission (IEC), the IEC 62443 series addresses the growing cybersecurity threats facing industrial control

systems (ICS) and critical infrastructure. It provides a comprehensive framework of standards and guidelines to help organizations secure their industrial processes against cyber-attacks. The scope of IEC 62443 standard is illustrated in figure 24 below:

Figure 24: Scope of IEC 62443 Standard

[Source: Industrial Ethernet Book][24]

8. **IEC 62714 (Engineering data exchange format):** Standardizes model-based data exchange for automation systems.

9. **ISO/IEC 27000 Series:** The series focuses on information security management systems, critical for protecting industrial data. This specification provides recommendations on information security management within the context of an Information Security Management System (ISMS). This standard covers privacy, confidentiality and IT, technical or cybersecurity issues. The overview of ISO/IEC 27000 series family is given below in figure 25:

[24] https://iebmedia.com/technology/industrial-ethernet/securing-industrial-automation-systems-using-iec-62443-4-2/

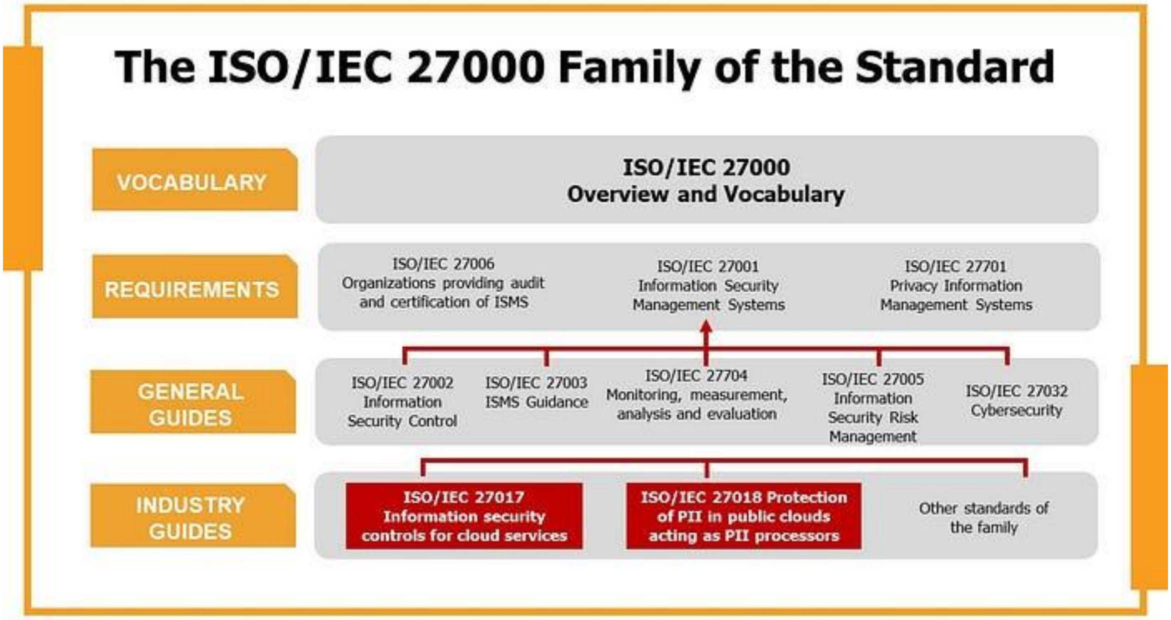

Figure 25: ISO/IEC 27000:2018 Overview

10. Standards Supporting Network:

a) Industrial Cables and Connectors

IEC 61156 series – Standards for twisted pair cables used in digital communications.

IEC 61156-5 covers cables for work areas with enhanced mechanical durability.

IEC 61754 – Defines fiber optic connector interfaces.

TIA/EIA-568 – Telecommunications cabling standard (specifies FTP/SFTP and performance parameters).

ISO/IEC 11801 – Generic cabling for customer premises.

IEC 61076-2-101 – Connectors for industrial environments (M12, RJ45 types).

b) Cable Length and Extension Practices

IEEE 802.3 (Ethernet Standard):

Specifies the 100-meter max length for standard Ethernet.

If exceeding, use switches or optical media converters.

IEC 61784-1 & -2 – Communication profiles for fieldbuses in industrial networks.

Recommends against the use of passive couplers in industrial environments.

c) Edge Computing / Edge Controllers

IEC 62264 / ISA-95 – Enterprise-Control System Integration:

Supports edge deployment architecture between control systems and MES/ERP layers.

ISO/IEC 30141:2018 – Internet of Things (IoT) Reference Architecture:

Recommends edge nodes for real-time and buffered data exchange.

OPC UA (IEC 62541) – Allows edge devices to function as data aggregators with context.

d) Machine Communication Classification

IEC 61131-3 – PLC programming interfaces and standards.

IEC 62453 (Field Device Tool/DTM) – Communication interfaces for partially compatible machines.

IEC 61784-5 – Profiles for field communication networks (Modbus, Profibus, DeviceNet, etc.)

IEEE 1451 – Standard for smart transducers, helps in bridging older equipment.

e) Wireless Network:

IEC 62657-2 – Guidelines for using wireless communication in industrial automation.

Includes assessment of wireless signal integrity in metallic environments.

IEEE 802.11 (Wi-Fi) – Standard for wireless LAN; but must be carefully evaluated for industrial usage.

IEC 61784-3 – Communication profiles for functional safety over wireless.

NIST SP 800-82 – Industrial Control Systems Security (wireless network hardening guidance).

11. **MTConnect:** MTConnect is an open, royalty-free standard that enables data exchange between manufacturing equipment and software applications to enhance production efficiency and monitoring. It provides a semantic vocabulary for manufacturing devices, facilitating seamless data collection and sharing to improve interoperability between machine tools, production systems, and manufacturing software. It is widely used for real-time machine data monitoring, equipment status tracking, process optimization and predictive maintenance. MTConnect supports smarter and more efficient manufacturing operations.

12. **ISO 14001:** Environmental management systems, ensuring sustainable industrial practices.

13. **STEP (ISO 10303):** It is a comprehensive ISO standard that describes how to represent and exchange digital product information.

14. **oneM2M:** oneM2M is a global standard for Machine-to-Machine (M2M) and Internet of Things (IoT) interoperability, enabling seamless communication and data sharing across devices, applications, and platforms. The important benefits of implementing oneM2M standards based solution includes interoperability of device & application; authentication & authorization of devices and Data security & Privacy. Figure 26 explains the features of oneM2M common service layer.

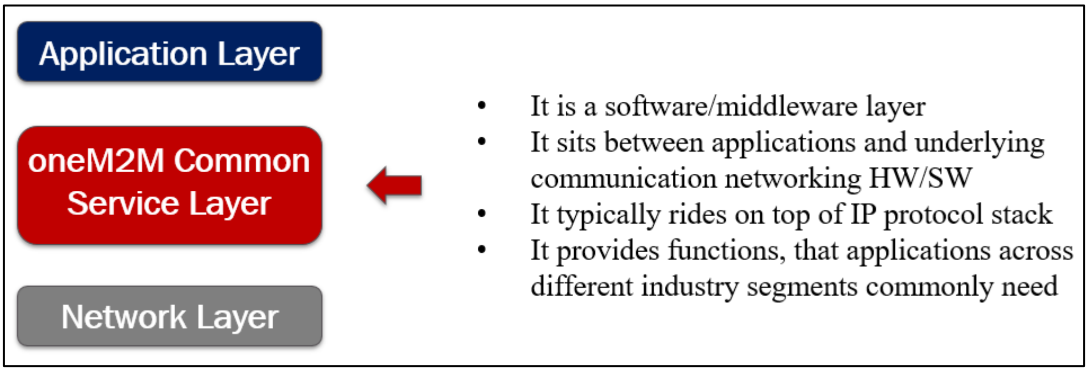

Figure 26: Features of oneM2M common service layer

15. **RAMI 4.0 (Reference Architectural Model Industry 4.0):** It is a three-dimensional model that helps visualize the relationships between various elements of Industry 4.0. Below figure 27 shows an overview of the Reference Architecture Model for Industry 4.0 (RAMI).

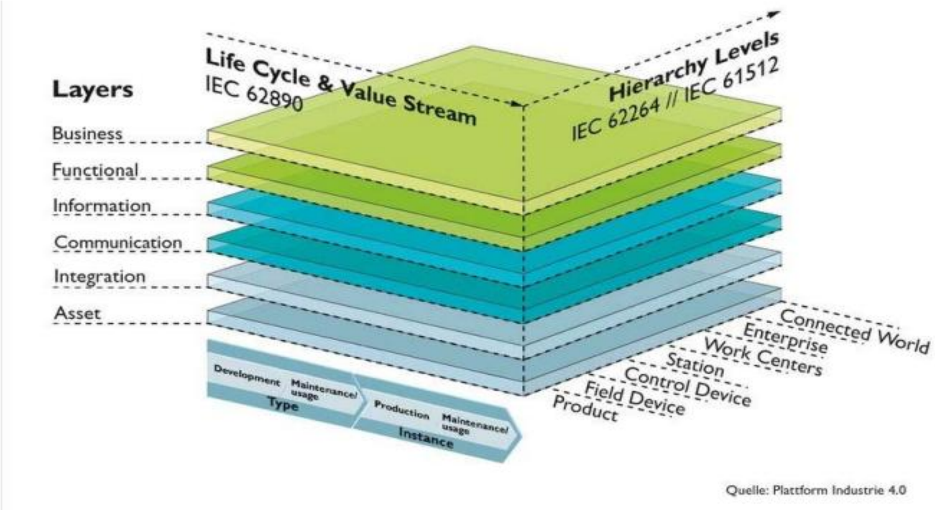

Figure 27: Reference Architecture Model for Industry 4.0

[Source: ETSI TR 103 507 V1.1.1][25]

This model is used for the alignment of several standards used in the aforementioned Industry 4.0 initiatives. These standards are grouped according to the topics they deal with that, in turn, are related to three key elements in the industry environment, i.e. factory, product and process. The standards related to the factory describe the organization, communication, structure and involvement in the development process of the machinery. The standards related to the product explain the hierarchy of the different products in the factory and both the communication between the different products and their relation with the machinery. Finally, the standards related to the process show the life-cycle of the products and the machinery.

[25] https://www.etsi.org/deliver/etsi_tr/103500_103599/103507/01.01.01_60/tr_103507v010101p.pdf

10. Global Adoption of Industry 4.0 Policy/ Standards

10.1. Global Smart Industry Readiness Index (SIRI) Initiative

The Global Smart Industry Readiness Index (SIRI) Initiative, led by the World Economic Forum in collaboration with the Singapore Economic Development Board, stands as a pivotal framework in the era of Industry 4.0. By offering a standardized methodology, SIRI enables manufacturers across various sectors and sizes to assess their digital transformation maturity comprehensively. Its structured approach evaluates three core building blocks Process, Technology, and Organization across 16 dimensions, facilitating a holistic understanding of a company's readiness for digital advancement. The Official SIRI Assessment (OSA), conducted by Certified SIRI Assessors, provides an independent evaluation, identifying high-impact areas for improvement and benchmarking against industry peers. This data-driven insight is crucial for manufacturers aiming to navigate the complexities of digital transformation, ensuring strategic alignment and resource optimization. The widespread adoption of SIRI, with over 850 assessments conducted globally, underscores its significance as a tool for fostering operational resilience and competitive advantage in the rapidly evolving industrial landscape.

10.2. Japan’s Society 5.0

Japan’s Industry 4.0 adoption is guided by the Society 5.0 initiative, introduced in April 2016 under the 5th Science and Technology Basic Plan. This initiative aims to go beyond digitalising the economy by addressing broader societal challenges such as an aging population and slow manufacturing growth. Society 5.0 leverages technologies like big data, IIoT, AI, and robotics to enhance manufacturing through flexible production planning, inter-plant coordination, efficient distribution, and customised product delivery. It focuses on enabling intelligent machines to generate knowledge from data, supporting the development of future industries and strengthening national innovation.

10.3. United States’ Initiatives

The U.S. Industry 4.0 initiative supports fundamental improvements in manufacturing, engineering, materials purchasing and supply chain management. The initiative is the product of several programs:

- The Advanced Manufacturing Partnership (2011) was a national effort that brought together representatives from industry, universities, and the federal government. Its goal was to identify challenges and opportunities to transform the technologies, products, and processes across several manufacturing industries.
- Launched in April 2014, the Advanced Manufacturing Partnership (AMP) 2.0 is a national effort to secure U.S. leadership in emerging technologies. It aims to create high-quality manufacturing jobs and enhance America’s global competitiveness.
- Ensuring Leadership in Advanced Manufacturing (2011) called for a partnership between government, businesses, and educators. The plan identified the most pressing manufacturing challenges and business opportunities.

- Capturing Domestic Competitive Advantage in Advanced Manufacturing (2012) described the policy opportunities and requirements of the United States as viewed from economic and national security perspectives.
- The National Strategic Plan for Advanced Manufacturing (2018) documents opportunities for federal policy to accelerate the development of advanced technologies in manufacturing.

10.4. European Initiatives

There are a number of initiatives around Smart manufacturing/industry 4.0 in Europe and in the Member States. The objective at the European level is to strengthen the coordination among the various initiatives and to facilitate the deployment of smart manufacturing at a Pan-European level, thus improving the competitiveness of the European manufacturing industry both in the Single Market and on a global scale and creating the conditions for the European technology providers to flourish.

i) Digitizing European Industry initiative (DEI)

In April 2016, the European Commission launched the Digitising European Industry initiative (DEI) as part of the Digital Single Market (DSM) strategy which aims to reinforce EU's competitiveness in digital technologies and to ensure that every business in Europe - whichever the sector, wherever located, whatever the size - can fully benefit from digital innovation.

ii) EU industrial strategy

On 10 March 2020, the European Commission launched a New Industrial Strategy for Europe, highlighting its overarching ambitions for the 'twin transition', a journey towards climate neutrality and digital transformation. The EU Industrial Strategy outlines three drivers for industrial transformation: global competition, climate neutrality, and a digital future.

The strategy is underpinned by a set of inter-connected and reinforcing elements:

a) certainty for industry and a deeper and more digital single market,
b) upholding a global level playing field,
c) a shift to climate neutrality,
d) building a more circular economy,
e) embedding industrial innovation,
f) skilling and re-skilling, and
g) investment and financing the transition.

iii) Vanguard Initiative

The Vanguard Initiative is a unique alliance that gathers 38 of the most advanced industrial regions in Europe, focused on stimulating industrial innovation and building European value-chains based on complementarities in regional smart specialisation strategies.

By connecting innovation ecosystems and sharing knowledge and facilities across its member regions, the Vanguard Initiative facilitates interregional collaboration, stimulates interregional innovation investments, strengthens open innovation, and speeds up the introduction and market-uptake of new products and innovations in Europe.

iv) Horizon Europe

Horizon Europe is the research and innovation support programme in a system of European and national funding programmes that share policy objectives. Under the pillar II of Horizon Europe, focuses on digital, industry and space and aims to deliver six ‘destinations’ matching the strategic plan (e.g. digital and emerging technologies for competitiveness and fit for the Green Deal; a human-centred and ethical development of digital and industrial technologies, etc.). The main area of interventions for this Cluster are among others:

- Artificial intelligence and robotics
- Advanced computing and Big Data
- Emerging enabling technologies and
- Space including earth observation.

v) National Initiatives:

Several European countries have also launched or are launching national initiatives to stimulate Industry 4.0 implementation. These initiatives include the following:

- Industrie 4.0 (Germany)
- Industry of the future (France)
- Smart Industry (Netherlands)
- Italy – Intelligent Factories, Industria 4.0
- Spain: Industria Conectada 4.0
- Slovakia – Smart Industry
- Austria: Plattform Industrie 4.0
- Poland: “Initiative for Polish Industry 4.0 – The Future Industry Platform”
- Portugal “Indústria 4.O”
- Lithuania: “Pramonė 4.0”
- Hungary: “IPAR 4.0 National Technology Platform”
- Czech Republic: “Průmysl 4.0”

National initiatives like these can have a positive effect on the market for Industry 4.0 services in these countries. They often invite companies to participate and give input on important subjects to make the transition easier.

11. Recommendations

11.1. Recommendations for the Ministry of Heavy Industries:

i. It is recommended that the Ministry of Heavy Industries (MHI) frame a comprehensive policy to formulate the Digitization Index to assess/monitor the level of digitization in traditional manufacturing industries with special focus on MSMEs/SMEs. As digitization plays a pivotal role in transitioning from traditional industries to Industry 4.0, the policy should focus on establishing a robust framework to assess and track the digital transformation progress of manufacturing sectors. This framework could include regular assessments, benchmarks/KPIs and tools for measuring digitization across various stages, from basic automation to the integration of advanced technologies like IoT, AI, and data analytics. By monitoring and promoting the digitization efforts of traditional industries, the policy can help accelerate the shift toward Industry 4.0 to enhance productivity and ensure global competitiveness.

ii. Since one of the identified key challenges for MSMEs is the setting up and maintenance of digital infrastructure it is recommended that MHI facilitates a dedicated Digital Infrastructure Cluster (DIC) that is designed to facilitate Industry 4.0 technologies for MSMEs. This cluster should include MSMEs, academic institutions (engineering institutions, polytechnics, and ITIs) and system integration companies. These stakeholders will collectively develop, implement and maintain the infrastructure while ensuring continuous learning and innovation. Reduced Capital Expenditure, Skilled Workforce Development, Improved Competitiveness, Data-Driven Decision Making can be some of the benefits of having such a DIC.

iii. A governing council could be formed to fund, monitor and ensure the operations of the DIC. The council will oversee the funding, assess the impact of the initiatives and ensure that the Software Defined Infrastructures (SDIs) are running efficiently. It will also provide governance and strategic direction to ensure that the clusters evolve in line with Industry 4.0 requirements.

iv. Additionally, it would serve best if a repository of best practices is built within the DIC. The repository will serve as a knowledge bank that MSMEs can tap into for solutions to common manufacturing challenges. These practices will cover processes like automation, data-driven decision-making, process optimization and more, enabling MSMEs to implement and scale Industry 4.0 technologies.

11.2. For Telecom Service Providers (TSPs):

i. It is recommended that Telecom Service Providers (TSPs) focus on offering tailored solutions that facilitate the growth of Industry 4.0 with a specific emphasis on Captive Network Private Network (CNPN) and network slicing. 5G and beyond technologies can provide high-speed, low-latency connectivity, essential for IoT, AI and Digital Twin based applications in Industry 4.0. TSPs should play an active role in supporting industries with scalable, secure and efficient communication infrastructures, enabling seamless integration of advanced technologies within manufacturing and other industrial sectors.

ii. In the context of a dedicated Digital Infrastructure Cluster (DIC) for MSMEs to adopt Industry 4.0 technologies, TSPs can play a critical enabling role. Their contributions could include providing High-Speed and Reliable Connectivity, Edge and Cloud Computing Services, Cybersecurity and Data Protection, IoT and Device Management Platforms, Infrastructure Co-investment and Leasing Models, Capacity Building, Technical support and Testbeds. By onboarding on the DIC, TSPs can become key enablers of MSME digital transformation, ensuring reliable, secure and scalable infrastructure aligned with Industry 4.0 imperatives. MHI could consider Public-Private-Partnerships (PPPs) with TSPs to institutionalize these contributions.

11.3. For Industries:

i. It is recommended that industries actively adopt TSPs solutions to expedite the growth and integration of Industry 4.0 technologies within their operations. By leveraging the advanced connectivity and network capabilities provided by TSPs, industries can enhance their productivity, efficiency and competitiveness. The adoption of 5G, private networks and other cutting-edge solutions like Network Slicing, will enable industries to better harness the full potential of IoT, AI, robotics and data analytics, driving the country’s transition to a digitally advanced industrial landscape.

ii. In the context of establishing a dedicated Digital Infrastructure Cluster (DIC) to promote Industry 4.0 adoption among MSMEs, large industries and corporations can play a pivotal role in strengthening the cluster ecosystem through strategic, technological and capacity-building contributions. Their involvement will accelerate MSME integration into modern value chains while fostering innovation and competitiveness. Their contributions could include Technology Sharing and Best Practices, Mentorship and Capability Building, Co-development and Innovation Ecosystems, Market Access and Supply Chain Integration, Infrastructure and Resource Sharing, Standardization and Policy Advocacy. By onboarding on the DIC ecosystem, industries can act as both catalysts and collaborators, accelerating the digital transformation in manufacturing sector. Their contributions, ranging from infrastructure to innovation, ensure that MSMEs are not only technology adopters but active participants in smart, resilient and globally competitive manufacturing networks.

11.4. For MSMEs:

i. To increase digital adoption among MSMEs, it is essential to address the four key barriers—Awareness, Availability of skilled resources, Accessibility, and Affordability. It is recommended to conduct focused awareness drives on how MSMEs can leverage Industry 4.0 solutions, which will also help build digital capabilities within their workforce. The government can offer subsidies for initial digital solution deployments, enabling MSMEs to gain confidence and creating success stories that inspire broader adoption. Additionally, platforms such as Centers of Excellence should be encouraged to connect MSMEs with startups and technology solution providers, offering cost-effective smart solutions and guidance on digital transformation. Digital Experience Zones can also be created to showcase live demos of Industry 4.0 technologies, helping MSMEs better understand their practical applications within factory settings.

ii. In the context of establishing a dedicated Digital Infrastructure Cluster (DIC) to enable Industry 4.0 adoption, MSMEs are not just beneficiaries, they are active contributors who can shape the relevance, effectiveness and sustainability of the cluster. Their practical insights, operational experience and commitment to innovation make them essential stakeholders in the ecosystem. Their contributions could include Use-Case Definition and Field-Level Insights, Co-development and Customization, Workforce Participation and Upskilling, Investment in Shared Infrastructure, Policy and Standardization Feedback and Local Ecosystem Development. MSMEs bring context, agility and entrepreneurial energy to the DIC ecosystem. By contributing practical knowledge, engaging in co-development and investing in capacity building, they ensure that the digital infrastructure evolves in a bottom-up, inclusive and sustainable manner. Their active participation is crucial to transforming the DIC into a living lab of continuous learning, innovation and scalable transformation.

11.5. Standards

It is recommended to adopt global standards related to Industry 4.0 to establish an interoperable and sustainable manufacturing ecosystem. Additionally, it is recommended to utilize oneM2M-based IoT platforms for the common service layer in IoT applications across various Industry 4.0 verticals. TEC has successfully adopted oneM2M Release 2 and 3 specifications as National Standards.

11.6. Mandatory Testing and Certification of Telecommunication Equipment(MTCTE)

It is recommended to ensure that IoT/ M2M devices or any other telecom products / equipment being used in verticals of Industry 4.0. should be tested and certified as per the Essential Requirement (ER) prepared for corresponding device under MTCTE regime. Security specifications, prepared in ITSAR (Indian Telecom Security Assurance Requirements) for IoT devices are also the part of ERs.

11.7. DoT vide office memorandum No. 4-10/2015-NT dated 08.02.2022 has mandated registration of M2M Service Providers(M2MSP) & WPAN/WLAN Connectivity Provider for IoT/ M2M Services on Saral Sanchar portal of DoT. Therefore, it is recommended to ensure that IoT/ M2M based solutions being implemented/ used/ planned in various sectors including industrial sector are provided by DoT-registered M2MSPs and WPAN/WLAN connectivity providers.

11.8. In the context of Industry 4.0, Programmable logic Controllers (PLCs), sensors and other baseline devices forms the foundational layer of IoT systems. Thus, there is a pressing need for continuous development of new sensors to meet evolving demands. To address these requirements, it is crucial to focus on the indigenous development of sensors.

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Appendix 1: Use Cases / Case Studies in Industry 4.0/Smart Manufacturing

With advent of 4G, 5G, AI and ML and reduction in costs for components, many Industry 4.0 use cases are seeing day of light. With Factories and mining at the core, Industry 4.0 use cases will not only lead to increased productivity and quality, but also result in safer operations.

A non-exhaustive list of use cases is given in the figure 28 below:

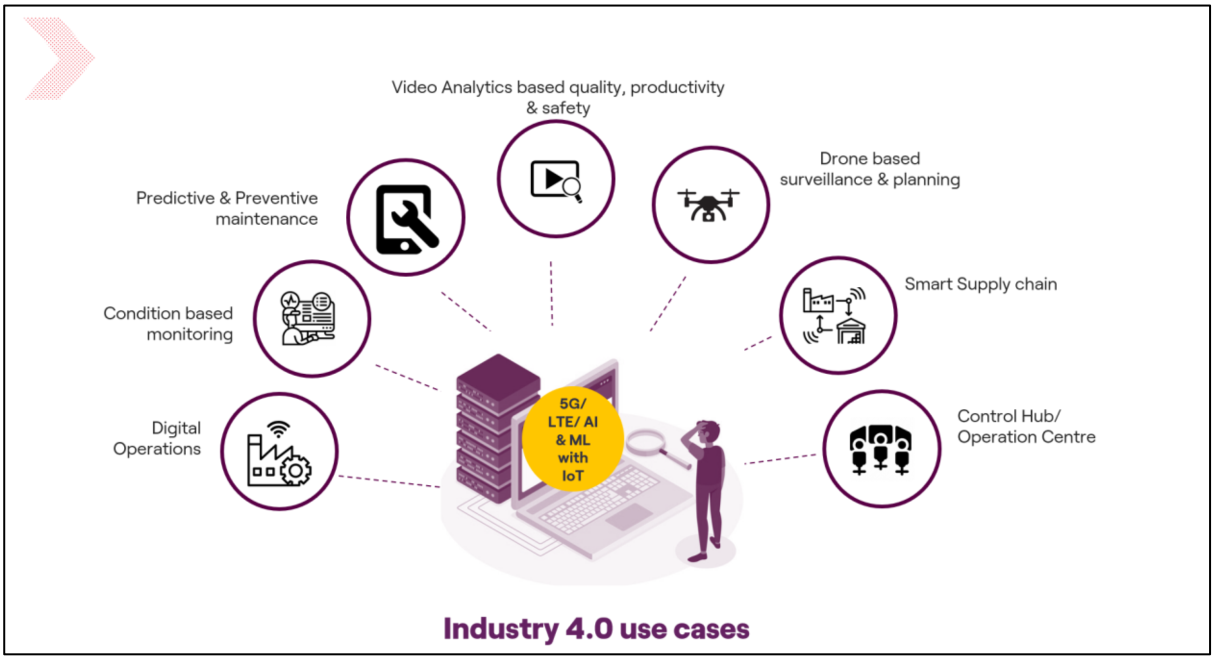

Figure 28: Industry 4.0 use cases

A1.1 Use Case 1: Factory visualization for production management

[Source: ITU-T Y.4003]

This system enables timely and appropriate decision-making at every level of enterprise management and factory management and unified visualization of information collected from multiple factories.

From the perspective of global expansion of production bases, supply chains and partner enterprises, it is important to improve production efficiency and to quickly respond to demand fluctuation and other situation changes in manufacturing processes. In addition, quick recovery when a factory loses its manufacturing ability is also important.

In this use case, a given product is manufactured in multiple factories. The factories can be located in various regions, including overseas and are interconnected.

The following information, categorized into five types – man, machine, material, method and environment (4M1E), is collected from multiple factories in real time:

- Man related information: operation of factory workers;

- Machine related information: equipment (repair history, process status);
- Material related information: expiration date, procurement information;
- Method related information: production time, maintenance time;
- Environment related information: power consumption.

This information is collected at one place in real time and analysed and visualized during the manufacturing process. The visualization enables timely decision making.

The overall system is required to handle various pieces of information, but some pieces of information should be provided to specific levels of the manufacturing enterprise.

Appropriate information for every level of the manufacturing enterprise can be provided through real-time visualization. For example, summary information for planning of a new factory set up or for making management decisions is provided to the enterprise manager. Production information for factory operation such as line-operating ratio, load factor and so on, is provided to the managers of the factories. Detailed information for improvement of the manufacturing sites is provided to individual factories. This system enables timely decision making by providing in real time the necessary information for every level of the manufacturing enterprise.

In addition, when a factory loses its manufacturing ability, this system enables quick recovery by using alternative production lines in other factories. It also enables adjustment of equipment parameters in the production lines according to the analysed information and enables a production line to be stopped by the prediction of malfunctions before production equipment is actually broken.

As a result, this system enables not only greater production efficiency but also strengthens quality, cost, delivery (QCD) competitiveness on the global stage.

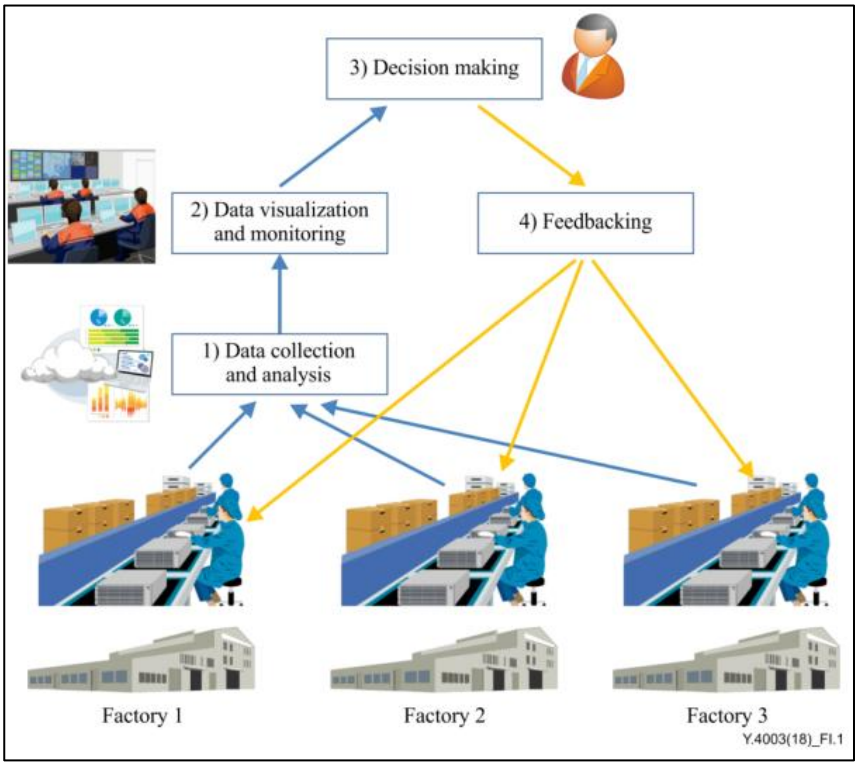

Figure 29: Factory visualization system for production management

[Source: ITU-T Y.4003]

The above illustrates the different operational phases of the factory visualization system as shown in Figure 29:

1. The manufacturing related data are collected from each factory and analysed;
2. The analysed data are visualized at one place for real-time monitoring;
3. An appropriate person (e.g., the enterprise manager) makes a timely decision regarding production management;
4. Instructions based on the decision are transferred to each factory.

A1.2 Use Case 2: Private LTE/5G based Digital Ops and Condition Based Monitoring

[Source: M/s VodafoneIdea, M/s Bevywise and M/s Nokia]

Digital Ops creates a sustainable framework to maximize asset utilization, equipment uptime and productivity. It also gives insights into machine health in a shop floor based on data of the machine condition and enables predictive maintenance.

The entire solution is powered by private 5G/ LTE that enables low latency, high reliability and secure solutions to take mission critical decisions at real time

Current Challenges that Digital Operations & Condition Based monitoring resolves:

- Poor decision making driven by limited insights of the shopfloor

- Increased unplanned downtime leading to loss of productivity
- Limited scalability of operations
- Reduced Safety oversight

Features of Digital ops & condition based monitoring:

- **Digitized Manufacturing operations:** Ensures efficient & safe handling and maneuvering/ planning of machinery and processes. With Digital twin, stakeholders can get complete insight of the production operations and take actions based on actionable insights given by the platform
- **Remote OEE & Productivity monitoring:** Processes data from factory floors to generate real time views of factory operations and production line output.
- **Condition based monitoring & predictive maintenance:** In a modern manufacturing environment, capital-intensive machinery such as AMRs (Autonomous Mobile Robots), cranes, and robotic systems play a critical role in shop floor operations. These assets are integral to material movement and internal logistics, making their availability crucial for ensuring a seamless and uninterrupted production flow.
- **Remote Asset monitoring**, powered by Industry 4.0 technologies—especially the Industrial Internet of Things (IIoT)—enables Original Equipment Manufacturers (OEMs) to monitor and track these machines in real time. It processes data points from sensors & machines and analyses with AI/ ML algorithm to predict future breakdowns.

This capability brings several strategic advantages:

- **Warranty Compliance and Usage Monitoring**: OEMs can collect operational data to validate warranty claims and detect any breaches in usage norms. This reduces disputes and ensures responsible usage of equipment.
- **Predictive and Proactive Maintenance**: Data collected via IoT sensors allows for predictive analytics, enabling early detection of anomalies. Maintenance can be scheduled before failure occurs, minimizing unexpected downtime.
- **Enhanced Equipment Lifecycle Management**: By tracking usage patterns and wear-and-tear data, OEMs and users can improve equipment care practices and extend operational lifespan.
- **Supply Chain Continuity**: For critical assets like cranes or AMRs that directly affect internal material movement, tracking ensures that any malfunction is identified early, preventing bottlenecks in the shop floor logistics and ensuring production continuity.
- **E-Logbook maintenance & management:** allows asset and operations management with real time tracking and maintenance management like E-logbook

These solutions have not just revolutionized manufacturing ops but have also shown proven applicability in mining operations where a whole digital twin of mines can be created for process planning, efficiency and safety.

Digital Replica of Factory Operations (Machines/Testers/Devices/Sensors Status in Real Time):

The digital replica of the factory, also known as a digital twin, is a virtual representation of the physical factory, its machinery, testers, devices and sensors, across its lifecycle, using real-time data to enable understanding, learning and reasoning. IoT sensors that gather information and data like real-time status, health and performance, live position, etc. are integrated with a physical object. Digital Twin ecosystem comprises of different technologies like IoT, AI, Big Data and cloud platform to enable this twin ecosystem. Thus, digital twin provides real-time insights into the operational status of machines, detecting performance metrics, potential malfunctions, or required maintenance. This proactive approach enhances the monitoring process and significantly reduces downtime, allowing for seamless factory operations.

Real-Time Decision Making and Control of Factory Operations:

With real-time data being continuously fed into the system, decision-makers can take quick and informed actions to optimize production. This real-time decision-making allows factory managers to adjust machine settings, reassign tasks, and even control operations remotely. The immediacy of data means the problems are solved before they escalate, improving factory throughput and reducing production delays.

Improved Efficiency and Productivity:

Real-time monitoring and decision-making contribute significantly to factory efficiency and productivity. Predictive maintenance prevents machine breakdowns, ensuring continuous production, while predictive analytics optimize workflow, reducing wastage and improving resource utilization. The insights provided help fine-tune operations, reducing energy consumption and maximizing output, thereby driving up productivity.

Scalable Architecture and Secure Global Accessibility:

The system is designed with scalability in mind, using cloud architecture for data aggregation and storage. This ensures secure global accessibility while offering a flexible, scalable infrastructure that can grow as the factory's operations expand. Integration with various platforms enhance connectivity, allowing seamless coordination between devices and systems across multiple locations.

Figure 30 below shows Digital Twin of a factory floor:

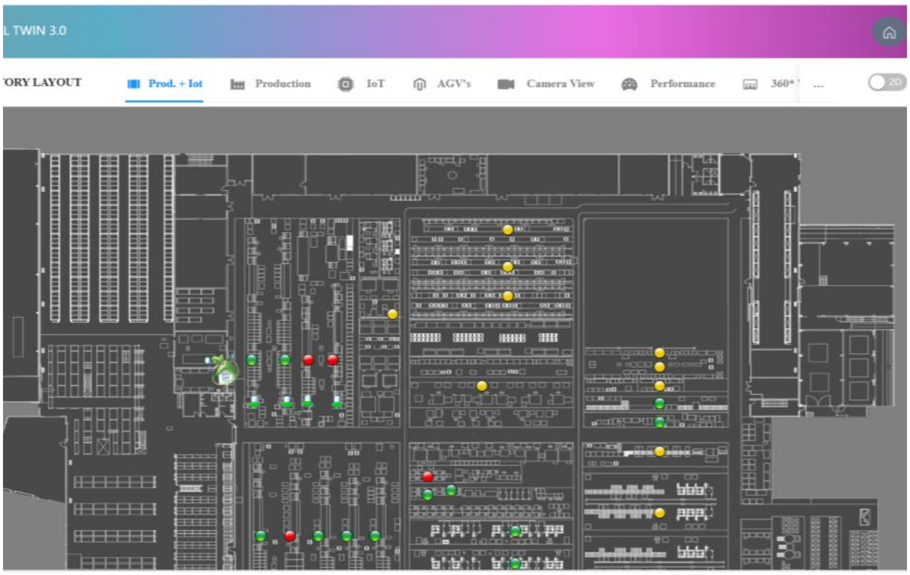

Figure 30: Digital Twin of a factory floor

Benefits of Digital Ops and Condition based monitoring:

- Improved uptime of up to 10-15%
- Improved performance of up to 10-15 %
- Improved productivity up to 15-20%
- Quality improvement by up to 5-10%
- Waste Reduction by up to 35-40%

A1.3 Use Case 3: 5G/ LTE based Drone surveillance

[Source: M/s VodafoneIdea]

5G/ LTE, AI/ML-driven drone solution enhances situational awareness and decision-making by rapidly capturing and analyzing critical industrial data. The drone can be affixed with various sensors as payloads as per the use cases or problem statement it is serving. The drone uses cellular network to send real time data to the server that can be used for real time decisions. In addition, data can be captured through cameras and sensors for later processing for use cases like survey and planning.

With 5G or LTE deployed in public or private mode, use cases brings high reliability and low latency of operational decisions resulting into higher efficiency and safety.

Drones can be used to monitor open cast or tunnel mines, warehouses and shopfloors. They can also be used to track assets and workers for efficiency and safety.

Current Challenges that 5G/ LTE powered Drone Surveillance resolves:

- Time consuming slow process of capturing data points for process and operations planning
- Inaccuracy and less precision in data measurements through manual approach
- Safety concerns and hazards that made it difficult for human resources to monitor assets
- Limited insights and visibility of operations that led to loss of productivity

Features:

- **Excavation Planning & Monitoring in Mining Operations:** LIDAR sensors for 3D modelling and planning through spatial insights
- **Remote Surveillance and monitoring of environment, asset and person:** RFID/ SONAR/ precision camera and other sensors for asset tracking and inventory stock keeping
- **Emergency Response Management:** Detects accidents, hazards, and gas leaks with minimal false alarms, enabling rapid response. AI powered analysis to render 3D images and give spatial insights

Benefits:

- Up to 100x faster operational efficiency.
- Up to 30% cost savings for economic operations.
- Up to 30% reduction in incidents for safer operations.
- Up to 20% reduction in environmental impact for sustainable operations.

A1.4 Use Case 4: AR based training and preventive maintenance

[Source: M/s VodafoneIdea]

Augmented reality (AR) is revolutionizing maintenance by enhancing training and enabling predictive maintenance strategies. AR overlays digital information onto the real world, providing technicians with real-time guidance, step-by-step instructions and access to critical data, improving efficiency and accuracy in both training and maintenance procedures.

The driving force of boom in mixed reality has been decrease in processing/ computation costs, advent of edge compute capabilities and lower data tariffs with low latencies and high reliability.

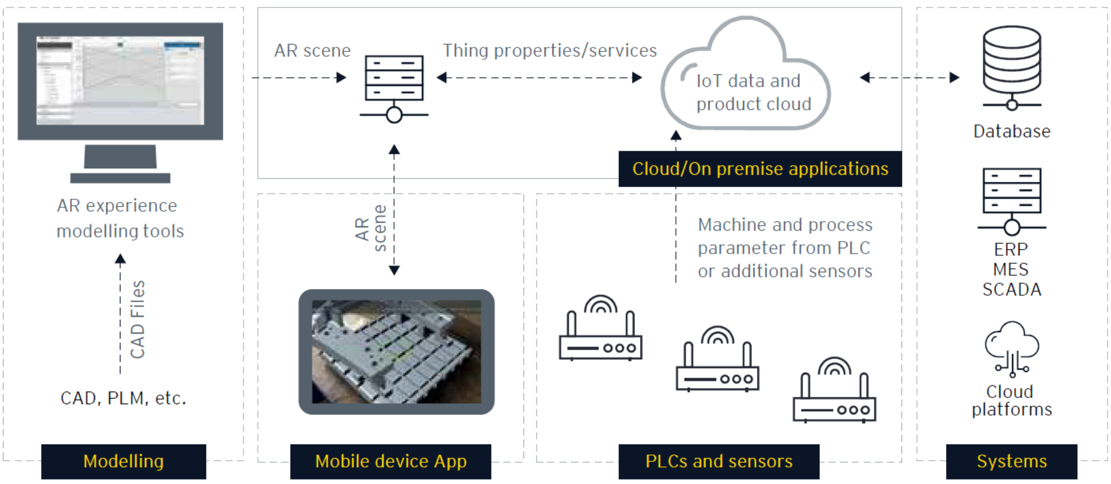

Figure 31: Generic IoT and augmented reality infrastructure

Figure 31 above provides an illustrative infrastructure setup for generic IoT and augmented reality. Virtual objects are recreated using computer aided design (CAD) tools to model the AR experience and scenes that are created. Equipment properties and services are exposed by IoT/Manufacturing Equipment Services (MES)/Supervisory Control and Data Acquisition (SCADA)/Enterprise Resource Planning (ERP) software and are merged with virtual objects. This is then superimposed on real-time feed of cameras to present an enriching user experience with contextual data superimposed on the recreated AR scenes on devices such as smartphone screens or AR headsets.

Current challenges this use cases addresses:

- Safety of personnel in hazardous areas when training happens in live environment.
- Requirement of highly skilled workers for preventive and predictive maintenance

Features:

- Realistic simulations with consistent training quality
- Performance tracking
- Insights derived from predictive and preventive maintenance

Benefits:

- Improved Training Retention
- Reduced Training Time
- Enhanced Safety Awareness
- Cost Savings
- Scalability

A1.5 Use Case 5: Video analytics based productivity, quality and safety

[Source: M/s VodafoneIdea]

This use case highlights benefits of real-time, high-definition video analytics for enhanced quality, security and efficiency, leveraging 5G for ultra-low latency and high bandwidth streaming. This solution includes use of 5G / LTE enabled camera with or without edge computing. The analysed information is visible on a cloud based application with actionable insights and alerts. This solution can enable monitoring and tracking of all kinds of assets and areas. Figure 32 shows high level flow of the solution:

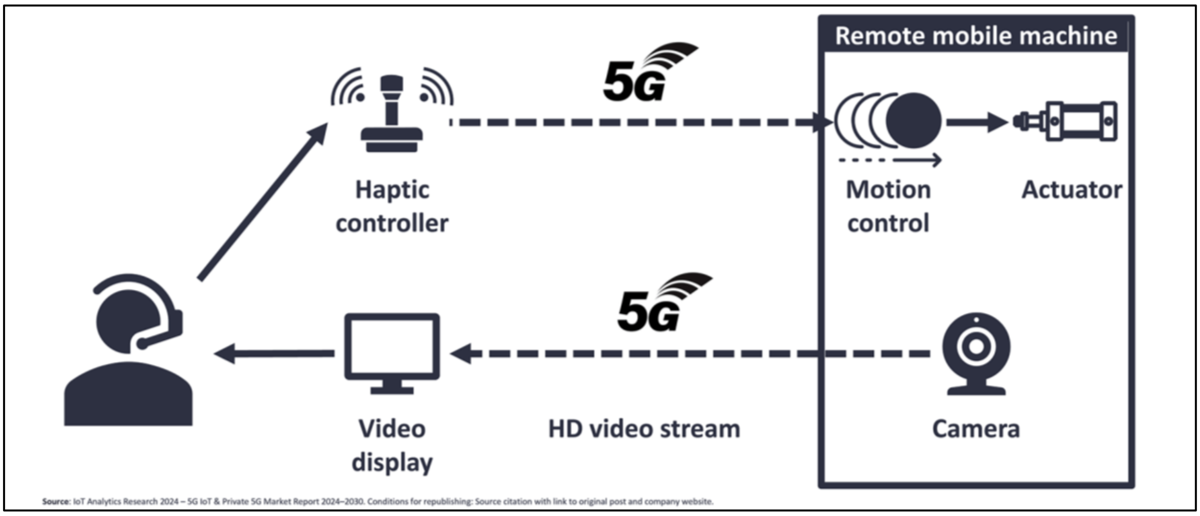

Figure 32: Simplified architecture of 5G-enabled remote control

Current challenges that this use case addresses:

- Low productivity because the worker is not on the workstations- real time monitoring not there.
- Manual quality inspections of good and material that is prone to errors.
- Frequent trespassing incidents in hazardous zones/ area of interest.
- Delayed accident response.

Solution features:

- Virtual fencing or area demarcation for trespassing prevention in hazardous area
- Asset or worker monitoring/ tracking
- Edge compute for real time alerts and accident response
- Auto detection of safety compliance breach events- safety gear non-compliance, fall/ accident detection.
- Visual Quality inspection/ monitoring- the quality of the processed material over assembly line is compared against a reference image of the material to ascertain no quality compromise.
- Cloud based dashboard for live monitoring as well as historical events playback.

Benefits:

- Up to 100x faster operational efficiency.
- Up to 30% cost savings for economic operations.
- Up to 30% reduction in incidents for safer operations.
- Up to 20% reduction in environmental impact for sustainable operations.

A1.6 Use Case 6: Smart Material Management: Pick to light/ Smart Supply chain

[Source: M/s Nokia]

Fully Wireless Operation powered by Private wireless connectivity and IoT

The factory's wireless operation is enabled by private wireless network for robust and reliable connectivity. Spare parts storage is integrated with IoT and data management is centralized in the cloud, ensuring seamless coordination of devices and real-time monitoring.

Pick-by-Light Solution for Spare Parts: For managing various types of spare parts, the pick-by-light system uses color-coded bins and slots to guide operators efficiently. This solution reduces first-response time by 95% during downtime support, ensuring rapid access to critical spare parts and minimizing delays in operations.

Sound and Light Enabled Poka-Yoke System: The system features location specific alarms with sound and light, guiding workers directly to the desired spare part. Colored LEDs at sub-slot locations provide a foolproof (Poka-Yoke) system, preventing human errors in spare part selection, further optimizing maintenance operations.

Reduction in Non-Value-Added (NVA) Time: With this system, non-value-added time spent in locating and identifying parts is eliminated, leading to a 30% reduction in Mean Time to Repair

(MTTR). This approach can scale to handle inbound and outbound material management systems, enhancing overall operational efficiency.

Figure 33: IoT Enabled Pick to Light

Supply chain and material movement enabled by Mobile Robots/ Automated Intelligent Vehicles (AIV) on shopfloor

AIVs help in factory operations by automating material handling, transportation, and logistics within the facility. AIV are advanced and capable of navigating autonomously (without requiring predefined paths) and suitable for tasks such as moving raw materials, components, or finished products across the production floor. AIVs use sophisticated sensors, to adapt to changing environments, avoid obstacles, and optimize routes in real time.

Enhanced Efficiency and Safety: AIVs help factory to improve operational efficiency. These vehicles reduce manual labour, streamline the flow of materials, and ensured timely delivery between workstations and departments. They also enhance safety by minimizing the risk of accidents in high-traffic areas, as they are equipped with sensors that detect and avoid human and obstacles.

Increased Flexibility and Scalability: AIVs are particularly beneficial for our factory's operations enabling flexibility since they can easily adapt to changes in layout or production demands more efficiently. They are integrated with existing factory systems, including inventory management and production scheduling, making them scalable for expanding operations on demand. This automation supports continuous production, minimizes downtime, and contributes to overall cost savings in logistics and material handling.

Figure 34: Mobile Robots/ Autonomous Intelligent Vehicles (AIVs)

A1.7 Use Case 7: Flexible Automation for Assembly Operations

[Source: M/s Nokia]

A Modular Automation Cell line integrates humans and machines to create a highly adaptable production environment. The system links various workstations wirelessly, enabling seamless communication and coordination between human workers and robots. This line allows for efficient handling of both complex and repetitive tasks while maintaining flexibility. Human workers collaborate with machines, contributing to tasks requiring precision and decision-making, while robots handle high-speed, repetitive processes. This fusion maximizes efficiency while maintaining quality across different production stages.

Customization Based on Product/Process Needs: The number of cells in the line is determined by the specific requirements of the product or process. The system allows for the use of either single or dual robots in a station, depending on the complexity and throughput requirement of the operation. Dual robots can work in tandem, completing multiple tasks in parallel, such as handling separate parts of a product simultaneously, increasing productivity and reducing cycle times.

Automation of Critical and Repetitive Tasks: Automation within the line focuses on processes that are both critical and repetitive, such as screw fixing, bullet assembly, 3D Automated Visual Inspection (AVI), and Auto Outgoing Goods Inspection (OGI). By automating these tasks, the system reduces human error, increases consistency, and enhances production speed.

Modularity/ Scaling Capacity Based on Demand: One of the standout features of the line is its modularity. Cells can be easily added or removed from the system, allowing factories to scale production capacity up or down based on demand. This plug-and-play functionality ensures that manufacturers can adapt quickly to market changes without overhauling the entire system.

Compatibility and Flexibility: Each cell is highly versatile, designed for compatibility across different processes by interchanging End of Arm Tooling (EOAT). This means that a single cell can perform various tasks, and combinations of dual robots (e.g., screw/bullet, inspection/screw) can be used to further streamline the process, making the line extremely adaptable to different manufacturing needs.

Figure 35 below gives a glimpse of Modular Automation Cells.

Figure 35: Modular Automation Cells

A1.8 Use Case 8: Environment Monitoring in Factory Operations: EMS & AQI

[Source: M/s Nokia]

EMS (Environment Management System):

The soldering of components onto Surface-mount technology (SMT) boards is carried out by automated Paste Printing Machine. However, even minor fluctuations in temperature and humidity inside the machine can affect the soldering process, leading to instability of components on the boards and compromising performance. With the new 5G boards containing a significantly higher number of components, any defects in soldering can result in quality issues and production delays. EMS is a system where sensors monitor and detect changes in temperature and humidity, alerting operators to address and resolve the issue promptly. After soldering, all boards undergo inspection by an optical machine, followed by a final check using a fully automated 3D inspection machine.

AQI (Air Quality Index):

Air Quality Index in a manufacturing factory is a critical metric for ensuring a safe and healthy environment for workers. The AQI measures the concentration of air pollutants, such as particulate matter (PM2.5 and PM10), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO) and volatile organic compounds, which can accumulate in factory settings due to machine's chemical processes.

In manufacturing environments, poor air quality can pose significant health risks to employees, leading to respiratory issues, irritation and long-term health complications. High levels of particulate matter can also impact the performance of sensitive machinery and equipment, potentially affecting production quality.

To maintain a safe AQI, factories typically implement advanced air filtration systems, use local exhaust ventilation and monitor pollutant levels with sensors to detect any rise in harmful gases or particulates. Strict adherence to occupational safety standards helps ensure that the indoor air quality remains within acceptable limits.

Continuous monitoring and control of AQI not only protect employee health but also contribute to overall operational efficiency, reducing downtime caused by health-related issues and ensuring compliance with environmental regulations.

A1.9 Use Case 9: Control Hub/ Smart Operations Center

[Source: M/s VodafoneIdea]

Control Hub is a smart hub for mining or manufacturing sites, for real-time monitoring, management, safety and efficiency. It integrates data for oversight, coordination, automation and operations improvement, offering real-time, bird's-eye view of all human and non-human assets. Utilizing cutting-edge technologies like 5G, AI/ML and IoT provides actionable insights for decision makers by processing and integrating data from surveillance cameras, sensors and equipment. This hub enables predictive management, minimizes risks to workers and enhances operational efficiency, leading to more sustainable and safe operations.

A control center, as shown in figure 36 below, has an array of screens that will have dashboard and live feeds from all the above use case that helps a shopfloor manager/ mining operations manager to take informed decisions.

Figure 36: A view of a Control Center

Current Challenges that this use cases addresses:

- Discrete information sources that make it difficult to take decisions
- Delayed accident response
- Poor communication
- Reduced productivity and efficiency

Solution features:

- Real time monitoring
- AI/ ML based actionable insights
- Communication integration for bi-directional instructions and updates
- Dashboarding of all operations

Benefits:

- Up to 30% reduction in operational costs
- Up to 30% increase in product quality
- Up to 20% increase in asset efficiency
- Up to 10% increase in safety and sustainability

A1.10 Use Case 10: Engine Manufacturer – Discrete Manufacturing

[Source: M/s Automation Industry Association (AIA)]

Background: This use case is implemented by Electrono Solutions Pvt Ltd for a global engine manufacturing company with a state-of-the-art diesel engine plant, which faced several digital integration challenges.

Challenges:

i. **Integration of Diverse Machinery:** The plant had a mix of advanced and legacy machines, including blowers and compressors, each with unique interfaces and data protocols. Integrating these into a unified system was technically complex.
ii. **Dynamic Operational Parameters:** Servo and spindle motors operate under varying loads. Defining fixed thresholds for monitoring wasn't viable. The system needed dynamic limits for current monitoring to reduce false alerts and better understand machine health.
iii. **Data Overload and Intelligence Generation:** With hundreds of data points per second across machines, the real challenge was not in capturing data, but in validating and interpreting it to generate actionable business intelligence.

Solutions Implemented:

i. **Unified Dashboard Creation:** All machines were digitally connected using a central platform. This included integration of blowers, compressors, coolant systems and other critical infrastructure.
ii. **Custom Signature Patterns:** Developed independent dynamic limit profiles for servo and spindle current signatures. These patterns were used as baselines to detect anomalies with greater precision.
iii. **Advanced Analytics Tool:** Traditional data analysis methods (like time-series and Fourier transforms) proved insufficient. The company implemented an advanced in-house analytics tool that could process voluminous data streams and extract real-time, actionable insights.

Results Achieved:

i. **Rapid ROI:** The company achieved return on investment within six months of deploying the solution.
ii. **Operational Improvements:** Real-time alerts (via SMS and email) improved response times to operational issues.

A1.11 Use Case 11: Vehicle Manufacturer – Discrete Manufacturing

[Source: M/s Automation Industry Association (AIA)]

Background: This use case is implemented by Electrono Solutions Pvt Ltd for an automotive and tractor manufacturer in India, part of a globally diversified conglomerate, sought to digitize and centralize operations across multiple factory locations.

Challenges:

i. **Multi-Location Integration:** Plants located in different parts of the country needed to be connected to a centralized digital command centre for performance monitoring and decision-making.
ii. **Digitizing Conventional Equipment:** Tool and die shops included old punch press machines with no digital interfaces.
iii. **Utilities and Equipment Integration:** The project required integrating overhead cranes and large compressors equipment traditionally monitored manually into the digital system.

Solutions Implemented:

i. **Centralized Data Infrastructure:** Plants from 6 different locations were connected across India to a single monitoring hub.
ii. **Legacy Equipment Digitization:** Retrofitted legacy machines with sensors and communication modules to feed data into the platform.
iii. **Utility Monitoring:** Installed wireless sensors on overhead cranes and compressors to track usage patterns and performance metrics in real time.

Results Achieved:

Seamless Deployment: The digital transformation was completed within the planned schedule and budget, with negligible downtime.

A1.12 Use Case 12: Two-Wheeler Manufacturer – Discrete Manufacturing

[Source: M/s Automation Industry Association (AIA)]

Background: This use case is implemented by Indxo AI Pvt Ltd for a two-wheeler manufacturer operating from a plant in South India, aimed to reduce production downtime and improve operational efficiency through data integration.

Challenges:

i. **Root Cause Analysis Deficiency:** Inconsistent machine failure logs made it difficult to trace the origins of failures, leading to extended downtime.
ii. **Tool Life Monitoring Issues:** Lack of insight into tool wear led to unexpected breakdowns and increased tooling costs.
iii. **Ineffective Safety Audits:** Manual logging of employee machine interactions resulted in unreliable safety audits.

Solutions Implemented:

i. **Machine Integration without IP Conflict:** Connected a wide variety of CNC machines (from different OEMs like Fanuc, Mitsubishi, Brother) to the same platform, without disrupting existing IP configurations.
ii. **High-Frequency Data Collection:** Real-time data sampling at 2 samples/sec allowed detection of micro-anomalies, aiding precise root cause analysis.
iii. **Tool Life Management System:** Automated tool wear monitoring was implemented. Alerts were triggered when tools neared end-of-life, enabling pre-emptive replacement.
iv. **Employee Audit Digitization:** Tablets with QR scanners were deployed. Workers scanned machine-linked QR codes, logging geo-location and time data automatically, improving audit traceability.

Results Achieved:

i. **Significant Cost Savings:** Identified a logic error in one machine that was causing system-wide downtime. Fixing it globally saved nearly $1 million.
ii. **Improved Efficiency:** The plant saw a 5% increase in OEE within eight months.

A1.13 Use Case 13: Automotive Lighting Manufacturer – Discrete Manufacturing

[Source: M/s Automation Industry Association (AIA)]

Background: A manufacturer in automotive lighting solutions, operating several manufacturing plants across India, wanted to digitize operations to improve production quality, track utilities, and integrate with ERP systems.

Challenges:

i. **Digitizing Injection Moulding Processes:** Needed to incorporate moulding operations into a digital ecosystem for real-time monitoring and control.
ii. **Non-Ethernet Controllers:** Some machines used outdated controllers with no Ethernet capability, making data collection difficult.
iii. **Utility Infrastructure Monitoring:** Required integration of multiple critical utilities like diesel generators, chillers, fire systems, and sewage treatment plants.
iv. **ERP – MES Integration:** Real-time production and utility data needed to be synced with ERP systems.
v. **FIFO Compliance:** Wanted a system to ensure First-In-First-Out handling of inventory to minimize storage inefficiencies and product aging.

Solutions Implemented:

i. **Sensor Deployment:** Deployed a wide range of custom sensors (temperature, vibration, voltage, etc.) tailored for each use case.
ii. **Energy Parameter-Based Monitoring:** Captured nearly 50 energy-related parameters to evaluate machine and utility performance.
iii. **Engineering-Focused Analytics:** Combined statistical and engineering analysis for deeper insights and higher data accuracy.
iv. **MES Connectivity:** All machine data was funneled into the MES, enabling end-to-end production traceability.
v. **Automated FIFO Enforcement:** Used camera systems and image processing to track parts and ensure FIFO was maintained, reducing operator dependency.

Results Achieved:

The system marked a major milestone in the organization’s digital transformation journey.

A1.14 Use Case 14: Flexible Manufacturing

[Source: ITU-T Y.4003]

This use case shows how one clothing enterprise can produce customized suits and personalized services according to the orders of each specific customer.

Flexible manufacturing realizes customized suits and personalized service by mass production in order to improve production efficiency, reduce production cost, shorten delivery time and also reduce the number of errors.

In this use case, a customer inputs his/her body-size data into the clothing enterprise's platform and selects the suit details from it, such as colour, size, fabric, buttons style, collar type, sleeve type, pocket design and so on. The platform automatically compares the customer's personal information with its stored data concerning specification sheet and available fabric pieces, converts into standard customization information and outputs a personalized order for the customer. At the same time, a three-dimensional (3D) model of the customized suit is displayed on the platform website, and the customers can there observe the suit's details. The customer can modify every detail of the output suit as he/she likes in real time. After this, each suit's production process is split into specific production lines by the intelligent production management software provided by clothing enterprise's platform, and the production lines are distributed to a given number of enterprise workers.

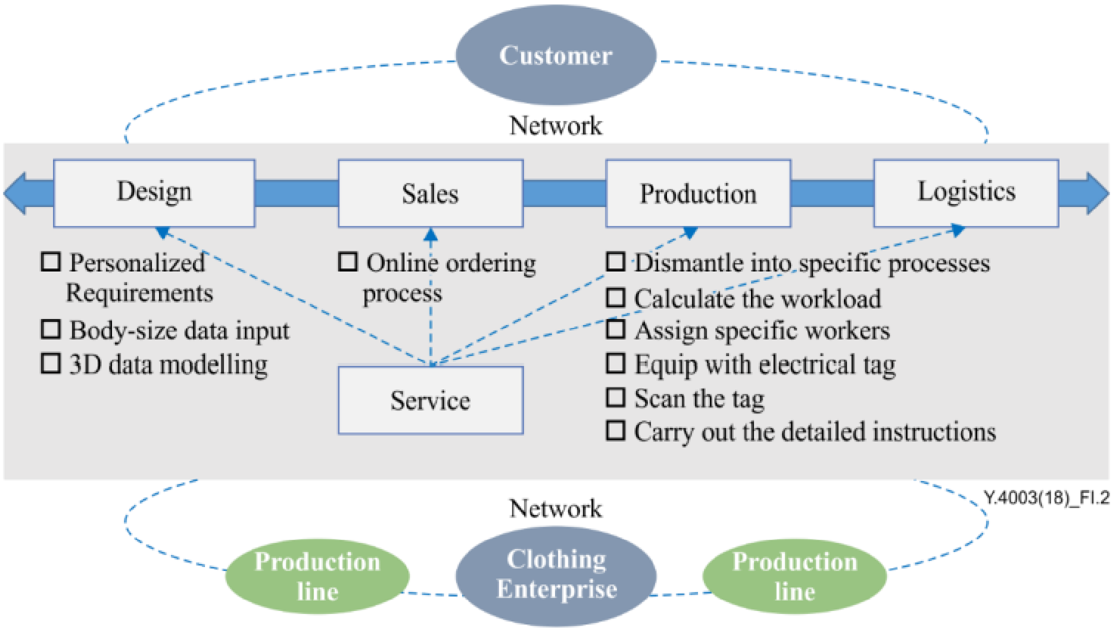

Figure 37: Summary view of flexible manufacturing

[Source: ITU-T Y.4003]

In this use case, shown in Figure 37, the steps of suit customization include design, sales, production and logistics procedures:

- During the design procedure, customer's body-size data and personalized requirements are at first collected into the clothing enterprise's platform and then the platform automatically matches the most appropriate version of the body size and forms a 3D model that is exclusive to the customer's personalized requirements. The platform then displays the 3D model of the customized suit on the website so that the customer can modify every detail of the suit to his/her satisfaction.
- During the sales procedure, the customer clicks on the platform website's order button. After this step, each ordered product acquires its own exclusive electronic tag.
- During the production procedure, the clothing enterprise's platform decomposes each suit's production into specific processes, i.e. suit materials' preparation process, specific cutting process, specific ironing process, specific sewing process, etc. Then it calculates the workload and the working hours for each process through the platform's analysis capabilities. After this step, each suit's production process is split into a number of production lines and the production lines are distributed to a specific set of workers based on the platform's analysis results. After this step, each cutting piece is equipped with an electrical tag and each working place is equipped with a tablet computer. Workers on the working place scan the tags of each piece of suit, then read the customer's requirements and carry out the detailed instructions according to the tablet computer instructions, e.g., sewing suits by hand or by machine for the lining, buttons, sleeve edge and so on.

- During the logistics procedure, the customized suit is transported to the customer after verification and packing of the completed suit.

During the whole suit customization process, each of the above procedures can be real-time monitored. With respect to the reference model of smart manufacturing in the context of the industrial IoT in the product life-cycle view, the set of the above procedures constitutes the service which is provided throughout the entire product life-cycle.

Appendix 2: Table of Abbreviations

S. No.	Abbreviation	Full Form
1.	3GPP	3rd Generation Partnership Project
2.	5G NR	5G New Radio
3.	6LoWPAN	IPv6 over Low Power Wireless Personal Area Networks
4.	AE	Applications Entities
5.	AI	Artificial Intelligence
6.	AIA	Automation Industry Association
7.	AIVs	Autonomous Intelligent Vehicles
8.	AM	Additive Manufacturing
9.	AMR	Autonomous Mobile Robots
10.	AQI	Air Quality Index
11.	AR	Augmented Reality
12.	AVI	Automated Visual Inspection
13.	BLE	Bluetooth Low Energy
14.	C4i4	Centre for Industry 4.0
15.	CA/DC	Carrier Aggregation
16.	CMTI	Central Manufacturing Technology Institute
17.	CNC	Computer Numerical Control
18.	CNPN	Captive Networks Private Networks
19.	CO	Carbon Monoxide
20.	CO_2	Carbon Dioxide
21.	COAP	Constrained Application Protocol
22.	CPSs	Cyber-Physical Systems
23.	CSE	Common Services Entities
24.	CSL	Common Services Layer
25.	C-V2X	Cellular Vehicle-to-Everything
26.	DEI	Digitizing European Industry initiative
27.	DIC	Dedicated Digital Infrastructure Cluster
28.	DL	Downlink
29.	DoT	Department of Telecommunications
30.	DR	Disaster Recovery
31.	DSL	Digital Subscriber Line
32.	DSM	Digital Single Market
33.	EDGE	Enhanced Data Rates for GSM Evolution
34.	eMBB	Enhanced Mobile Broadband
35.	EMS	Environment Management System
36.	eMTC / LTE-M	Enhanced Machine Type Communication / LTE Machine Type Communication
37.	eNodeB	Enhanced Node B
38.	EOAT	End of Arm Tooling
39.	ER	Essential requirement
40.	ERP	Enterprise Resource Planning
41.	ETSI	European Telecommunications Standards Institute

42.	EU	European Union
43.	eURLLC	Enhanced Ultra Reliable Low Latency Communications
44.	FDM	Fused Deposition Modeling
45.	FIFO	First In, First Out
46.	FSK	Frequency Shift Keying
47.	FTP	Foil Twisted Pair
48.	FTTH	Fiber to the Home
49.	GPRS	General Packet Radio Service
50.	GSM	Global System for Mobile Communications
51.	HMI	Human Machine Interface
52.	HSDPA	High Speed Download Packet Access
53.	HSPA	High-Speed Packet Access
54.	HSPA+	Evolved High-Speed Packet Access
55.	HTTP	Hyper Text Transfer Protocol
56.	IaaS	Infrastructure as a Service
57.	IAB	Integrated Access and Backhaul
58.	IACS	Industrial Automation and Control Systems
59.	IAM	Identity and Access Management
60.	ICS	Industrial Control Systems
61.	ICT	Information and Communication Technology
62.	ID	Unique Identifier
63.	IEC	International Electrotechnical Commission
64.	IEEE	Institute of Electrical and Electronics Engineers
65.	IIoT	Industrial Internet of Things
66.	IMS	IP-based Multimedia Services
67.	IMT	International Mobile Telecommunications
68.	IoS	Internet of Services
69.	IoT	Internet of Things
70.	IP	Internet Protocol
71.	IPE	Interworking Proxy Entities
72.	IPv6	Internet Protocol version 6
73.	ISA	International Society of Automation
74.	ISM	Industrial, Scientific, and Medical
75.	ISMS	Information Security Management System
76.	IT	Information Technology
77.	ITI	Industrial Training Institutions
78.	ITSAR	Indian Telecom Security Assurance Requirements
79.	ITU	International Telecommunication Union
80.	KPI	Key Performance Indicator
81.	LAN	Local Area Network
82.	LoRa	Long Range
83.	LoRaWAN	Long Range Wide Area Network
84.	LPWA	Lowest Complexity for Wide- Area Deployments
85.	LPWAN	Low Power Wide Area Network
86.	LTE	Long Term Evolution
87.	M2M	Machine-to-Machine

88.	MES	Manufacturing Executive System
89.	MFA	Multi-Factor Authentication
90.	MHI	Ministry of Heavy Industries
91.	MIMO	Multiple Input Multiple Output
92.	MiR	Mobile Industrial Robots
93.	ML	Machine Learning
94.	mMTC	Massive Machine Type Communication
95.	mmWave	Millimeter Wave
96.	MQTT	Message Queuing Telemetry Transport
97.	MSME	Micro, Small, and Medium Enterprises
98.	MTConnect	Machine Tool Connect
99.	MTCTE	Mandatory Testing and Certification of Telecommunication Equipment
100	MTTR	Mean Time to Repair
101	MV	machine vision
102	NAN	Neighbourhood Area Network
103	NB-IoT	Narrowband IoT
104	NDCP	National Digital Communications Policy
105	NFC	Near Field Communication
106	NFV	Network Functions Virtualization
107	NIST	National Institute of Standards and Technology
108	NR	New Radio
109	NR NTN	New Radio – Non-Terrestrial Networks
110	NR V2X	New Radio Vehicle-to-Everything
111	NR-Light	New Radio – Light
112	NR-U	New Radio Unlicensed
113	NSA	Non-Standalone
114	NTN IoT	Non-Terrestrial Network Internet of Things
115	NVA	Non-Value Added
116	ODVA	Open DeviceNet Vendors Association
117	OEM	Original Equipment Manufacturer
118	OFDMA	Orthogonal Frequency Division Multiple Access
119	OGI	Outgoing Goods Inspection
120	OPC	Open Platform Communications Unified Architecture
121	OPC-UA	Open Platform Communication Unified Architecture
122	OSA	Official SIRI Assessment
123	OSI	Open Systems Interconnection
124	OT	Operational Technology
125	PaaS	Platform as a Service
126	PAN	Personal Area Network
127	PCs	Personal Computers
128	PLC	Programmable Logic Controllers
129	PM	Particulate Matter
130	POS	Point of Sale
131	PPP	Public-Private Partnerships
132	QCD	Quality, Cost, Delivery

133	QoS	Quality of Service
134	RAMI	Reference Architectural Model Industry
135	RBAC	Role Based Access Control
136	RedCap	Reduced Capability
137	RF	Radio Frequency
138	RFID	Radio Frequency Identification
139	ROI	Return on Investment
140	RTU	Remote Terminal Unit
141	SA	Standalone
142	SaaS	Software as a Service
143	SAE	System Architecture Evolution
144	SAMARTH	Smart Advanced Manufacturing and Rapid Transformation Hub
145	SDN	Software-Defined Networking
146	SFTP	Shielded Foil Twisted Pair
147	SIRI	Smart Industry Readiness Index
148	SLA	Service Level Agreements / Stereolithography
149	SLS	Selective Laser Sintering
150	SMEs	Small and Medium-sized Enterprises
151	SMT	Surface Mount Technology
152	SO2	Sulfur Dioxide
153	SON	Self-Organizing Networks
154	SSD	Solid State Drive
155	STEM	Science, Technology, Engineering and Mathematics
156	TCP	Transmission Control Protocol
157	TDD	Time Division Duplex
158	TD-SCDMA	Time Division-Synchronous Code Division Multiple Access
159	TIA	Telecommunication Industry Association
160	TSP	Telecom Service Providers
161	UAV	Unmanned Aerial Vehicles
162	UDP	User Datagram Protocol
163	UE	User Equipment
164	UL	Uplink
165	UMTS	Universal Mobile Telecommunications System
166	UNS	Unified Namespace
167	uRLLC	Ultra-Reliable Low Latency Communications
168	USOF	Universal Service Obligation Fund
169	VR	Virtual Reality
170	WAN	Wide Area Network
171	Wi-Fi	Wireless Fidelity
172	Wi-Fi 6E	Wi-Fi 6 Extended
173	WLAN	Wireless Local Area Network
174	WPAN	Wireless Personal Area Networks

Appendix 3: References

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Appendix 4: List of Working Group (WG) meetings

S. No.	Date of the virtual meeting of WG
1.	1st Meeting: 28th August 2024
2.	2nd Meeting: 26th September 2024
3.	3rd meeting: 13th November 2024
4.	4th Meeting: 18th February 2025
5.	5th Meeting: 18th March 2025
6.	6th Meeting: 23rd April 2025
7.	7th Meeting: 26th May 2025

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