

Role of Smart Manufacturing in Industry 4.0

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Abstract

Smart manufacturing integrates advanced digital technologies, such as sensors, the industrial Internet of Things and cloud computing, into traditional manufacturing processes. Its adoption leads to increased efficiency and agility in factory operations, as well as improved resiliency and sustainability. Industry 4.0 refers to the broader Fourth Industrial Revolution, following mechanization, mass production and automation. Smart manufacturing is considered as a key component of the transition to Industry 4.0; the terms are often used interchangeably. Smart manufacturing, however, typically focuses on the technologies required to produce goods more efficiently, reliably and flexibly at the factory level. This study is based on the secondary data. The following are the objectives of the study 1.to study What is smart manufacturing? 2. to identify the core technologies of smart manufacturing 3.to study about the benefits of smart manufacturing services 4.to assess impact of digital transformation in reshaping manufacturing in industry 4.0 5.to find out the challenges in building the smart factories.

Keywords – Smart Manufacturing, Industry 4.0, Technologies

Introduction

Smart manufacturing is revolutionizing the industrial landscape, enabling factories to become more agile, efficient, and innovative. Discrete manufacturers today face the challenge of producing more product variants in smaller quantities while maintaining operational efficiency and quality standards. Supply chain resilience has become a board-level priority due to various external factors that have highlighted the threat to business continuity. Smart manufacturing provides a roadmap for addressing these challenges by leveraging connected technologies, real-time data, AI-driven insights, and automation. By adopting smart factory solutions, manufacturers can enhance supply chain transparency, improve the connection between design and manufacturing, enhance utilization and delivery performance while staying competitive in a rapidly evolving market¹. This paper will explore about the key aspects of smart manufacturing including core technologies of smart manufacturing and about the benefits of smart manufacturing services and impact of digital transformation in reshaping manufacturing in industry 4.0.

Objectives of the study

- to study about the smart manufacturing and its characteristics.
- to identify the core technologies of smart manufacturing.
- to study about the benefits of smart manufacturing services.
- to assess impact of digital transformation in reshaping manufacturing in industry 4.0.
- to identify the challenges in building the smart factories and how to overcome them.

Methodology of the study

Fundamental or basic research design has been used in the study data. For this study secondary data has been collected from various online journals and websites.

What is Smart Manufacturing?

Smart manufacturing is the integration of advanced digital technologies with traditional processes to deliver the critical information needed to improve decision-making, increase efficiency, reduce costs, and boost agility. Smart manufacturing replaces outdated, rigid systems with connected, cloud-based technology that operates collaboratively with workers and adapts to the current and future needs of the business. A variety of technologies are necessary for smart manufacturing, including internet-connected devices and sensors that collect and communicate real-time data. That data is used to optimize manufacturing processes and workflows, uncover areas for automation, predict equipment maintenance needs, respond promptly to market changes and ensure product quality.

Key aspects of smart Manufacturing

- Smart manufacturing creates connected, data-driven production environments through the use of networked industrial devices and equipment, real-time data collection and adaptable processes.
- It makes possible cutting-edge technological approaches for optimizing production capabilities, such as collaborative robots, digital twins and augmented reality.
- With smart manufacturing, data-driven insights inform better decision-making to help manufacturers achieve strategic goals, such as innovation, growth, cost reduction and sustainability.
- Successfully adopting smart manufacturing requires more than technology — it demands investing in the digital skills and data literacy necessary for workers to effectively leverage smart manufacturing capabilities².

Core Technologies of Smart Manufacturing

Smart manufacturing (SM) is a sophisticated process, dependent on a network of new technologies working collaboratively to streamline the entire production ecosystem. Key smart manufacturing tools include the following:

Industrial Internet of Things (IIoT)

The IIoT is a network of interconnected machinery, tools and sensors that communicate with each other and the cloud to collect and share data. IIoT-connected assets help industrial manufacturing facilities manage and maintain equipment by utilizing cloud computing and facilitating communication between enabled machinery. These features use data from multiple machines simultaneously, automate processes and provide manufacturers more sophisticated analyses.

In smart factories, IIoT devices are used to enhance machine vision, track inventory levels and analyse data to optimize the mass production process.

The IIoT not only allows internet-connected smart assets to communicate and share diagnostic data, enabling instantaneous system and asset comparisons, but it also helps manufacturers make more informed decisions about the entire mass production operation.

Artificial intelligence (AI)

One of the most significant benefits of AI technology in smart manufacturing is its ability to conduct real-time data analysis efficiently. With IoT devices and sensors collecting data from machines, equipment and assembly lines, AI-powered algorithms can quickly process and analyse inputs to identify patterns and trends, helping manufacturers understand how production processes are performing.

Companies can also use AI systems to identify anomalies and equipment defects. Machine learning algorithms and neural networks, for instance, can help identify data patterns and make decisions based on those patterns, allowing manufacturers to catch quality control issues early in the production process.

Furthermore, utilizing AI solutions as a part of smart maintenance programs can help manufacturers:

- Implement predictive maintenance
- Streamline supply chain management
- Identify workplace safety hazard

Robotics

Robotic process automation (RPA) has been a key driver of smart manufacturing, with robots taking on repetitive and/or dangerous tasks like assembly, welding and material handling. Robotics technology can perform repetitive tasks faster and with a much higher degree of accuracy and precision than human workers, improving product quality and reducing defects.

Robotics are also extremely versatile and can be programmed to perform a wide range of tasks, making them ideal for manufacturing processes that require high flexibility and adaptability. At a Phillips plant in the Netherlands, for example, robots are making the brand's electric razors. And a Japanese Fanuc plant uses industrial robots to manufacture industrial robots, reducing personnel requirements to only four supervisors per shift.

Perhaps most significantly, manufacturers interested in an SM approach can integrate robotics with IIoT sensors and data analytics to create a more flexible and responsive production environment.

Cloud and Edge computing

Cloud computing and edge computing play a significant role in how smart manufacturing plants operate. Cloud computing helps organizations manage data collection and storage remotely, eliminating the need for on-premises software and hardware and increasing data visibility in the supply chain. With cloud-based solutions, manufacturers can leverage IIoT applications and other forward-thinking technologies (like edge computing) to monitor real-time equipment data and scale their operations more easily.

Edge computing, on the other hand, is a distributed computing paradigm that brings computation and data storage closer to manufacturing operations, rather than storing it in a central cloud-based data centre. In the context of smart manufacturing, edge computing deploys computing resources and data storage at the edge of the network—closer to the devices and machines generating the data—enabling faster processing with higher volumes of equipment data.

Edge computing in smart manufacturing also helps manufacturers do the following:

- Reduce the network bandwidth requirements, latency issues and costs associated with long-distance big data transmission.
- Ensure that sensitive data remains within their own network, improving security and compliance.
- Improve operational reliability and resilience by keeping critical systems working during central data centre downtime and/or network disruptions.
- Optimize workflows by analysing data from multiple sources (e.g., inventory levels, machine performance and customer demand) to find areas for improvement and increase asset interoperability.

Together, edge computing and cloud computing allow organizations to utilize software as a service (SaaS), expanding technology accessibility to a wider range of manufacturing operations.

In manufacturing environments, where delays in decision-making can have significant impacts on production outcomes, cloud computing and edge computing help manufacturing companies quickly identify and respond to equipment failures, quality defects, production line bottlenecks, etc.

Blockchain

Blockchain is a shared ledger that helps companies record transactions, track assets and improve cybersecurity within a business network. In a smart manufacturing execution system (MES), blockchain creates an immutable record of every step in the supply chain, from raw materials to the finished product. By using blockchain to track the movement of goods and materials, manufacturers can ensure that every step in the production process is transparent and secure, reducing the risk of fraud and improving accountability.

Blockchain can also be used to improve supply chain efficiency by automating many of the processes involved in tracking and verifying transactions. For instance, an organization can utilize smart contracts—self-executing contracts with the terms of the agreement written directly into lines of code—to verify the authenticity of products, track shipments and make payments. This can help reduce the time and cost associated with manual processes, while also improving accuracy and reducing the risk of errors.

Manufacturers can also utilize blockchain technologies to protect intellectual property by creating a record of ownership and improve sustainability practices by tracking the environmental impact of production processes.

Digital twins

Digital twins have become an increasingly popular concept in the world of smart manufacturing. A digital twin is a virtual replica of a physical object or system that is equipped with sensors and connected to the internet, allowing it to collect data and provide real-time performance insights. Digital twins are used to monitor and optimize the performance of manufacturing processes, machines and equipment.

By collecting sensor data from equipment, digital twins can detect anomalies, identify potential problems, and provide insights on how to optimize production processes. Manufacturers can also use digital twins to simulate scenarios and test configurations before implementing them and to facilitate remote maintenance and support.

3D printing

3D printing, also known as additive manufacturing, is a rapidly growing technology that has changed the way companies design, prototype and produce products. Smart factories primarily use 3D printing to manufacture complex parts and components quickly and precisely.

Traditional manufacturing processes like injection moulding can be limited by the complexity of a prototype's part geometry, and they may require multiple steps and operations to produce. With 3D printing, manufacturers can produce complex geometries in a single step, reducing manufacturing time and costs.

3D printing can also help companies:

- Develop customized products and components by using digital design files.
- Build and test prototypes right on the shop floor.
- Enable on-demand manufacturing to streamline inventory management processes.

Predictive analytics

Smart manufacturing relies heavily on data analytics to collect, process and analyse data from various sources, including IIoT sensors, production systems and supply chain management systems. Using advanced data analytics techniques, predictive analytics can help identify inefficiencies, bottlenecks and quality issues proactively.

The primary benefit of predictive analytics in the manufacturing sector is their ability to enhance defect detection, allowing manufacturers to take pre-emptive measures to prevent downtime and equipment failures. Predictive analysis also enables organizations to optimize maintenance schedules to determine the best time for maintenance and repairs³.

Benefits of Smart Manufacturing

As manufacturers continuously strive to be more cost effective, energy efficient and sustainable, smart manufacturing is becoming essential. Indeed, the White House has designated smart manufacturing as one of four critical and emerging technologies (CETs) that make up the field of advanced manufacturing and are deemed vital for national security. The other three are additive manufacturing, clean and sustainable manufacturing, and nanomanufacturing.

The benefits of smart manufacturing can be grouped into four main categories: operational improvements, quality enhancements, cost and efficiency savings, and strategic advantages.

Operational Improvements

Smart manufacturing represents a fundamental shift in how manufacturing systems operate. Some of the key operational improvements it has brought about include:

- **Enhanced productivity:** Smart manufacturing boosts productivity by integrating interconnected systems that automate and optimize factory operations, leading to increased output. The collection and analysis of data in real time — whether about equipment performance, production flow or inventory levels — help managers understand what's going on and then make adjustments to keep production running apace.
- **Enhanced efficiency:** Real-time monitoring, data analysis and automation streamline production processes and workflows for fast product turnaround. These capabilities also help reduce waste, maximize resources (machines and workers) and minimize energy consumption, all of which collectively lead to cost savings and leaner manufacturing operations.
- **Overall equipment efficiency (OEE):** Operational efficiency in manufacturing is achieved, in part, by maximizing the number of outputs with the least amount of waste (think: time, materials, equipment usage and other resources). OEE is a manufacturing key performance indicator that tracks the percentage of time the company is producing high-quality products relative to downtime, such as when equipment is being repaired. Put another way, OEE measures actual productivity.
- **Optimized assets:** Manufacturers spent nearly \$238 billion on equipment in 2022, according to the most recent data from the U.S. Census Bureau. Through proactive, real-time monitoring and analysis, smart manufacturing makes sure these assets are operating at their peak. This data also helps to improve equipment utilization and reliability by predicting maintenance needs and reducing downtime.
- **Maximum flexibility:** Another smart manufacturing benefit comes from the visibility it provides across manufacturing processes and the supply chain. This allows for quick adaptation to changes in demand, supply-chain variability, production requirements and business strategies. Production output and schedules can be dynamically updated and inventory can be managed more effectively, for example. This high level of responsiveness improves overall operational performance.

Quality Enhancements

The importance of quality in manufacturing cannot be overstated, whether referring to the quality of internal processes or of products. Smart manufacturing is tied to:

- **Enhanced quality control:** Quality control focuses on the processes, workflows and techniques that lead to consistent production of superior products. By tracking OEE, for example, manufacturers can pick up on a bottleneck in the production line and take corrective actions that result in a more reliable manufacturing process.
- **Improved product quality:** Smart manufacturing raises product quality through use of precision technologies, such as computer numerical control (CNC) machining and 3D printing, that ensure each product adheres to the highest standards.

These systems continuously monitor production, instantly detecting and fixing even the slightest deviations, resulting in higher-quality end products.

- **Reduced errors:** The automation of tasks not only eliminates human errors, but real-time data from sensors about equipment health helps ensure that machines are functioning optimally, reducing the likelihood of product defects. Corrective actions can be applied before goods proceed to their next stage or are shipped to customers, which reduces costs associated with rework and returns, boosts customer satisfaction and builds a positive brand reputation.

Cost and Efficiency Savings

Smart manufacturing saves companies significant amounts of money by automating processes, optimizing energy use and minimizing waste.

- **Cost reduction:** By automating processes, enhancing efficiency and reducing waste and energy consumption, smart manufacturing technologies help manufacturers reduce their operational costs. Of course, smart manufacturing itself requires a financial investment, but, as a result, nearly two-thirds of manufacturers expect to become more competitive and build business resilience over the long term, according to the Rockwell report.
- **Predictive maintenance:** Predictive maintenance harnesses the power of real-time data to anticipate equipment failures before they occur. This foresight enables timely maintenance of machinery — before the need for expensive repairs — thereby extending their life span and protecting manufacturers' initial investments.
- **Reduced downtime:** Predictive maintenance also minimizes the costs of unplanned production halts. By proactively identifying and troubleshooting equipment issues, manufacturers are able to maintain a steady production flow, which is crucial for operational efficiency and cost savings.

Strategic Advantages

Smart manufacturing can help companies achieve broader business goals, from standing out in a crowded marketplace, to top-line growth or a stronger bottom line.

- **Beyond continuous improvement:** Manufacturers must be nimble, quickly adjusting to changes like fluctuating raw material costs or shifts in product demand. Smart manufacturing not only streamlines manufacturers' processes for continuous improvement but also goes beyond — to improve profitability and overall cost structures, foster innovation and competitive differentiation, and drive growth and business expansion.
- **Management and transparency:** By collecting data throughout the supply chain, on the factory floor and in the warehouse, smart manufacturing provides a clear, data-derived picture of the entire manufacturing process. This paves the way for all of the operational gains discussed throughout this article and for more effective management, as well. Companies can also use this data to demonstrate regulatory compliance and to better plan and manage their processes, ensuring more efficient and responsive operations.
- **Sustainability:** Smart manufacturing is key for companies aiming to establish eco-friendly practices and streamline resource use, including energy and water conservation. It also supports the creation of circular supply chains that minimize waste and promote recycling. This approach is not only beneficial for the environment, but it also makes good business sense: U.S. consumers say they are willing to pay a premium for sustainable products — 11%, on average, according to a Bain & Co. report. Moreover, executives surveyed for that report expect that circular products and services will increase their revenue by an average of 30% by 2030⁴.

How digital transformation is reshaping manufacturing in Industry 4.0

Digital transformation is not just a trend—it's a necessity for manufacturers aiming to stay competitive in an increasingly technology-driven world. The integration of digital technologies into manufacturing processes is creating a widening performance gap between digital leaders and laggards. With a data-driven approach to production, companies can:

- **Enhance operational efficiency** – Digital tools like IoT-enabled sensors, AI-driven analytics, and cloud-based automation help manufacturers optimize production lines, reduce downtime, and streamline supply chains. Predictive maintenance powered by AI can detect equipment failures before they occur, minimizing costly disruptions.
- **Improve product quality and customization** – Advanced data analytics and AI allow manufacturers to monitor quality in real time, ensuring that defects are caught early. Technologies like digital twins enable precise simulations, reducing errors and enabling the creation of highly customized products tailored to specific customer needs.
- **Enable intelligent factories and industry 4.0** – The concept of Industry 4.0 revolves around interconnected intelligent factories where machines communicate seamlessly using IoT and AI. This leads to higher levels of automation, greater production flexibility, and a more agile response to market demands.
- **Reduce costs and waste** – By leveraging technologies such as cobots, autonomous and mobile robots, manufacturers can optimize resource utilization, reduce energy consumption, and minimize material waste. Through digital monitoring and smart resource allocation, sustainable manufacturing practices become more achievable.
- **Strengthen supply chain resilience** – Digital transformation provides real-time supply chain visibility, allowing manufacturers to track inventory, forecast demand, and respond proactively to disruptions. Blockchain technology enhances transparency and security in transactions, reducing risks of fraud and inefficiencies.

- **Enhance workforce productivity and safety** – Automation and augmented reality tools assist workers in complex tasks, reducing human errors, increasing productivity and addressing skills shortages. Wearable technologies and AI-driven safety protocols enhance workplace safety by monitoring hazardous conditions and providing instant feedback.

Industry 4.0 represents the next chapter in industrial evolution, highlighting the transition from adaptive manufacturing to autonomous manufacturing, increasing efficiency and productivity through intelligent, interconnected factories.

Adaptive manufacturing, while a significant advancement over traditional manufacturing methods, relies on human intervention and predefined rules to respond to changes in production processes. This approach, though valuable, is inherently limited by the speed and flexibility of human decision-making and the constraints of rule-based systems.

On the other hand, autonomous manufacturing, facilitated by advancements in AI, machine learning, and Industrial IoT technologies, introduces a new paradigm where manufacturing systems can self-optimize, predict outcomes, and make real-time decisions with minimal human intervention.

This transition enables discrete manufacturers to achieve new levels of efficiency by automating routine tasks, reducing downtime through predictive maintenance, and dynamically allocating resources to meet changing production demands. As discrete manufacturers navigate this shift Siemens automated production operations and production line engineering solutions have emerged as a pivotal enabler of digital transformation⁵.

Challenges in Building the Smart Factories and How to Overcome Them

The Path to a Smarter Factory is Not Always Smooth

The promise of the smart factory is compelling: a hyper-efficient, data-driven environment that boosts productivity, reduces costs, and enhances agility. With 86% of manufacturers believing smart factory initiatives will be the main driver of competitiveness in the next five years, the question is no longer *if* but *how* to make the transition.

However, the journey from a traditional plant to a fully integrated smart factory is filled with significant hurdles. Many organizations find themselves struggling with high costs, complex technology integration, and a workforce unprepared for the digital shift. In fact, many initiatives fail to move beyond the pilot stage, a phenomenon known as “pilot purgatory”. This article identifies the five biggest challenges of smart factory implementation, supported by industry research, and provides a practical guide on how to overcome them.

High Initial Investment and Unclear ROI

The Challenge: The upfront cost of implementing smart factory technologies—from IoT sensors and software platforms to new machinery—can be substantial. For many executives, especially in small and medium-sized enterprises (SMEs), justifying this large capital expenditure without a clear and immediate Return on Investment (ROI) is a major barrier.

How to Overcome It:

- **Start Small and Scale:** Instead of a factory-wide overhaul, begin with a pilot project in a high-impact area. Focus on a single production line or a critical bottleneck where improvements can be quickly measured.
- **Focus on OEE:** Use Overall Equipment Effectiveness (OEE) as a key metric. A simple Machine Monitoring System (MMS) can track downtime and inefficiencies, providing clear data to prove the value of further investment.
- **Adopt a Modular Approach:** Choose solutions that are modular and scalable. This allows you to add capabilities over time as you achieve positive ROI, controlling costs and minimizing risk.

Integrating Legacy Systems (IT/OT Convergence)

The Challenge: Most factories are “brownfield” environments, meaning they operate with a mix of old and new equipment from various manufacturers, each with its own proprietary protocols. Integrating these legacy Operational Technology (OT) systems with modern Information Technology (IT) infrastructure is a complex technical nightmare. This lack of interoperability creates data silos and prevents the seamless flow of information needed for a truly smart factory.

How to Overcome It:

- **Use IoT Gateways:** Implement IoT gateways and protocol converters that can translate data from older machines (using protocols like Modbus) into a standard format (like MQTT) for modern IT systems.
- **Centralized IoT Platform:** Deploy a centralized platform that can connect to diverse assets, regardless of their age or vendor. This creates a unified data layer for the entire factory.
- **Prioritize Data Standardization:** Establish a clear data governance strategy from the beginning to ensure all information collected is consistent, accurate, and usable across different applications.

The Talent Gap and Workforce Resistance

The Challenge: A smart factory requires a workforce with new skills in data analytics, AI, and robotics. According to Deloitte, the talent gap is a top concern for manufacturers, with many struggling to find and retain qualified employees. Furthermore, existing employees may resist change, fearing that automation will make their jobs obsolete. This cultural resistance can sabotage even the most well-designed digital transformation strategy.

How to Overcome It:

- **Invest in Reskilling and Upskilling:** Create internal training programs to equip your current workforce with the necessary digital skills. Focus on turning machine operators into "data interpreters."
- **Promote Human-Machine Collaboration:** Frame the transformation not as a replacement of people, but as an augmentation of their abilities. Emphasize how technology can eliminate repetitive, tedious tasks, allowing employees to focus on higher-value problem-solving.
- **Engage Employees Early:** Involve factory floor staff in the planning and implementation process. Their hands-on knowledge is invaluable for identifying practical challenges and ensuring the new tools are user-friendly.

Cybersecurity Vulnerabilities

The Challenge: As factories become more connected, their "attack surface" expands dramatically. Every IoT sensor, machine, and network connection is a potential entry point for cyber threats. A successful attack on a smart factory can go beyond data theft; it can halt production, damage expensive equipment, compromise worker safety, and disrupt the entire supply chain.

How to Overcome It:

- **Adopt a "Defence-in-Depth" Strategy:** Implement multiple layers of security, including firewalls, intrusion detection systems, and network segmentation to isolate critical OT systems from the general IT network.
- **Prioritize Access Control:** Enforce strict role-based access control and multi-factor authentication to ensure only authorized personnel can access or modify sensitive systems.
- **Regular Security Audits and Training:** Conduct regular vulnerability assessments and provide ongoing cybersecurity training for all employees to build a security-conscious culture.

Data Overload and Failure to Scale

Data Overload and Failure to Scale

The Challenge: Smart factories generate an enormous amount of data. Without a clear strategy, companies risk "drowning in data" without extracting any meaningful insights (4). This is a key reason why many companies get stuck in "pilot purgatory"—they can successfully run a small-scale trial but fail to scale it across the enterprise because the data management and analytics capabilities are not robust enough (2).

How to Overcome It:

- **Define Clear Business Goals:** Before collecting any data, define the specific business problems you want to solve. This ensures you only gather relevant data and can measure the impact of your initiatives.
- **Leverage Edge and Cloud Computing:** Use edge computing to process time-sensitive data locally on the factory floor, reducing latency. Send summary and historical data to the cloud for more complex analysis and long-term storage.
- **Utilize AI-Powered Analytics:** Implement AI and machine learning platforms that can automatically analyze large datasets to identify patterns, predict failures, and provide actionable recommendations, turning raw data into business intelligence.

How TMA Solutions Helps You Overcome These Hurdles

The journey to a smart factory is a marathon, not a sprint. At TMA Solutions, we provide a modular and scalable approach to help you navigate these challenges effectively.

Our **T-Connect IoT platform** is designed to solve the integration problem, seamlessly connecting legacy and modern equipment into a single, unified dashboard. It provides the foundation for data collection and management, helping you move beyond pilot projects to a factory-wide deployment. Paired with our Machine Monitoring System (MMS), you can start small, prove ROI quickly, and build momentum for your digital transformation. We empower you to turn data into a strategic asset, ensuring your smart factory initiative delivers tangible business value from day one⁶.

Conclusion

While implementing a smart factory presents significant challenges, they are not insurmountable. By adopting a strategic, phased approach that focuses on clear business outcomes, invests in people, and prioritizes security and scalability, manufacturers can successfully navigate the complexities of digital transformation.

The goal is not just to build a factory that is "smart," but one that is resilient, agile, and prepared for the future. With the right strategy and the right technology partner, these challenges become opportunities to build a lasting competitive advantage⁷.

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