www.ijecs.in
International Journal Of Engineering And Computer Science
Volume 13 Issue 10 October 2024, Page No. 26504-26522
ISSN: 2319-7242 DOI: 10.18535/ijecs/v13i10.4922

IoT and Edge Computing for Smart Manufacturing: Architecture and Future Trends

Sunthar Subramanian [1]

[1] Director - IoT & Sustainability - Smart Manufacturing

Abstract

The integration of the Internet of Things (IoT) and Edge Computing is revolutionizing the manufacturing industry, ushering in the era of smart manufacturing as part of Industry 4.0. This paper explores the synergy between IoT and Edge Computing, focusing on their combined architecture and the future trends driving innovation in smart factories. IoT enables the connection and communication of machines, sensors, and systems, allowing for real-time data collection and monitoring. However, traditional cloud-based approaches face challenges such as latency, bandwidth limitations, and security risks, which can hinder real-time decision-making in fast-paced manufacturing environments. Edge Computing addresses these issues by processing data closer to the source, minimizing latency, and reducing dependence on cloud infrastructures. By combining IoT and edge solutions, smart manufacturing systems can make faster, data-driven decisions, improving efficiency, reliability, and operational flexibility. This paper delves into the architectural design of IoT and edge computing in manufacturing, outlining how data flows from IoT devices to edge nodes and cloud services. Several real-world use cases and industry examples are analyzed to highlight the practical benefits of these technologies. Additionally, this research identifies key challenges such as security vulnerabilities, the need for robust network infrastructures (e.g., 5G), and issues related to data standardization. The future of smart manufacturing is also explored, emphasizing trends like the adoption of artificial intelligence (AI) and machine learning (ML) at the edge, digital twins for real-time monitoring, and the role of IoT and edge computing in fostering sustainability through energy-efficient production processes. This study provides a comprehensive overview of IoT and edge computing architectures in smart manufacturing and offers insights into future technological trends that will shape the industry.

1. Introduction

The convergence of the Internet of Things (IoT) and Edge Computing has revolutionized modern industrial practices, giving rise to what is known as Smart Manufacturing. This transformation is essentially a part of the ongoing Industry 4.0 movement, which emphasizes using advanced digital technologies to improve manufacturing efficiency, flexibility, and productivity. By connecting machines, systems, and human operators through interconnected networks, IoT enables real-time data collection and sharing. Meanwhile, Edge Computing brings the ability to process this vast amount of data closer to the physical devices, reducing latency and reliance on centralized cloud systems.

Centralized data processing through cloud platforms has been the norm in traditional manufacturing environments. While this approach works for some use cases, the increasing need for real-time processing and control has exposed its limitations. For instance, transmitting large volumes of data to the cloud can introduce significant delays, particularly in time-sensitive applications such as predictive maintenance, quality control, and robotics. Edge Computing, by contrast, allows data to be processed locally, at or near the source of data collection, ensuring faster response times and improved system reliability.

1.1. Problem Statement

Smart manufacturing environments face a significant challenge: managing the massive amounts of data generated by IoT devices in real time while ensuring that systems operate reliably and with minimal latency. Centralized cloud-based models struggle to meet these demands, especially when dealing with high-bandwidth applications such as autonomous machines, real-time analytics, and digital twins. Edge Computing offers a solution by decentralizing processing, but integrating it effectively with IoT remains complex.

1.2 Importance of IoT and Edge Computing in Smart Manufacturing

The role of IoT and Edge Computing in manufacturing goes beyond simple automation. These technologies enable data-driven decision-making and offer unprecedented insights into production processes. IoT devices collect data from machines, sensors, and production lines, feeding critical information into analytical models that can predict equipment failures, optimize resource utilization, and improve product quality. By utilizing Edge Computing, these insights can be generated and applied in real-time, directly on the factory floor, without sending data to distant servers. This allows manufacturers to be more agile, reduce operational downtime, and make informed decisions faster.

Furthermore, Edge Computing addresses two significant concerns in smart manufacturing: latency and bandwidth. With data being processed locally, manufacturers can avoid the delays associated with sending data to cloud platforms. Moreover, edge systems reduce the strain on network bandwidth by filtering and analyzing data at the source, transmitting only the most critical information to the cloud or other centralized systems for long-term storage and further processing.

1.3 Objectives of the Paper

This paper aims to explore the architectural integration of IoT and Edge Computing in smart manufacturing environments, providing insights into how these technologies can be deployed to optimize industrial operations. Additionally, the paper aims to analyze future trends and developments, particularly focusing on how emerging technologies such as 5G, Artificial Intelligence (AI), and Machine Learning (ML) are expected to shape the future of smart manufacturing.

To achieve these objectives, the following areas will be discussed in depth:

- An overview of IoT and its application in smart manufacturing.
- The role of Edge Computing and its advantages over traditional cloud computing.
- The architectural design of IoT and Edge Computing in a smart manufacturing ecosystem.
- Benefits, challenges, and limitations of integrating these technologies.
- Future trends will drive the adoption and evolution of IoT and Edge Computing in manufacturing.

By addressing these critical areas, the paper will provide a comprehensive understanding of the technological advancements that are paving the way for the next generation of smart factories. In particular, the combination of IoT and Edge Computing offers new opportunities for manufacturers to enhance efficiency, sustainability, and competitiveness in a rapidly evolving global market.

2. IoT in Smart Manufacturing

2.1 Overview of IoT in Manufacturing

The Internet of Things (IoT) is a network of interconnected physical devices communicating and exchanging data without human intervention. In the context of smart manufacturing, IoT technologies enable factories to optimize processes by integrating sensors, actuators, machines, and systems. These devices capture real-time data, allowing the manufacturers to monitor operations, control machines, and manage production remotely. IoT-driven manufacturing aims to increase operational efficiency, reduce downtime, and enhance product quality through automation and data-driven decision-making.

The convergence of IoT with smart manufacturing is a critical component of Industry 4.0, which focuses on the digital transformation of traditional manufacturing. Smart factories employ IoT to automate processes, reduce human error, and create a more flexible production environment. By connecting equipment, IoT enables the continuous monitoring of assets, leading to predictive maintenance, improved asset management, and optimized supply chains.

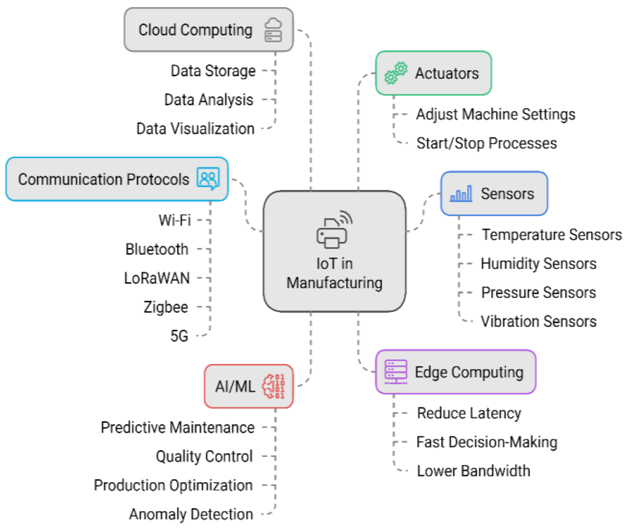
2.2 Benefits of IoT in Manufacturing

IoT technologies offer numerous advantages in the manufacturing sector, which are vital for achieving smart factory objectives:

1. **Predictive Maintenance:** IoT sensors collect real-time data on equipment and machinery's condition, identifying issues before they cause system failures. This data helps implement predictive maintenance strategies, reducing downtime and extending the lifespan of equipment. Predictive maintenance is an evolution from traditional preventive maintenance, where servicing occurs based on actual usage and condition data rather than fixed schedules.
2. **Enhanced Operational Efficiency:** IoT automates many manual tasks and processes, increasing operational efficiency. IoT-enabled systems continuously monitor production lines and optimize workflows by adjusting operations based on real-time data. This reduces bottlenecks and increases production throughput.
3. **Energy Efficiency:** IoT sensors can track energy consumption in real-time and adjust the machines' operations accordingly. Manufacturers can implement energy-saving measures, minimize waste, and achieve sustainability targets with detailed insights into how energy is used.
4. **Inventory Management:** IoT enables better tracking and management of inventory throughout the production process. Sensors and RFID tags can provide real-time information about stock levels, movement of goods, and raw materials. This helps companies to optimize their just-in-time (JIT) manufacturing processes, reducing storage costs and ensuring that materials are available when needed.
5. **Quality Control:** IoT devices can monitor production conditions and detect abnormalities, such as temperature fluctuations or machine vibrations, that could affect product quality. Real-time alerts allow operators to address issues before they impact the final product, reducing defects and waste.
6. **Supply Chain Optimization:** IoT extends beyond the factory floor, enabling better integration with suppliers, distributors, and logistics companies. Real-time tracking of shipments, inventory levels, and production materials increases supply chain transparency, reducing delays and inefficiencies.

2.3 Key Components of IoT in Smart Manufacturing

IoT in smart manufacturing involves several critical components, each playing a distinct role in the overall system:



Graph 1: Components of IoT in Smart Manufacturing

Sensors: IoT sensors are deployed across various points in the manufacturing process to collect data on machinery, environmental conditions, and products. These sensors monitor temperature, humidity, pressure, vibration, and other parameters, which can be used to optimize operations or trigger alarms when thresholds are breached. For example, vibration sensors can detect early signs of machine wear, allowing for timely maintenance.

1. **Actuators:** Actuators are responsible for executing actions based on data collected by sensors. They enable automation by interacting with machinery to adjust machine settings or start and stop processes. In smart manufacturing, actuators are often controlled through real-time IoT systems that respond to changing conditions or machine states.
2. **Communication Protocols:** IoT devices communicate with each other and with centralized systems (like cloud platforms) using various communication protocols. These include Wi-Fi, Bluetooth, LoRaWAN, Zigbee, and 5G. Each protocol has different bandwidth, range, and power consumption characteristics, making some better suited for low-power devices and others for high-speed data transmission. 5G, in particular, is a promising technology for IoT in manufacturing, as it offers low-latency, high-speed communication, ideal for real-time data processing and control in smart factories.
3. **Edge Computing:** In smart manufacturing environments, edge computing is often used with IoT devices to process data locally rather than send all information to the cloud. By doing so, edge computing reduces latency, allows for faster decision-making, and reduces bandwidth requirements. This is particularly important in manufacturing scenarios where real-time responses are critical for maintaining operational efficiency.
4. **Cloud Computing:** IoT systems in manufacturing rely on cloud platforms for data storage, analysis, and visualization. While edge computing handles real-time processing, cloud computing is used for in-depth analytics, machine learning, and long-term data storage. The cloud provides scalability, enabling managing vast amounts of data generated by IoT devices.
5. **Artificial Intelligence (AI) and Machine Learning (ML):** IoT-generated data can be fed into AI and ML algorithms to extract valuable insights. In smart manufacturing, AI and ML are used for predictive maintenance, quality control, production optimization, and anomaly detection. These technologies enable factories to adapt and improve continuously based on data-driven insights.

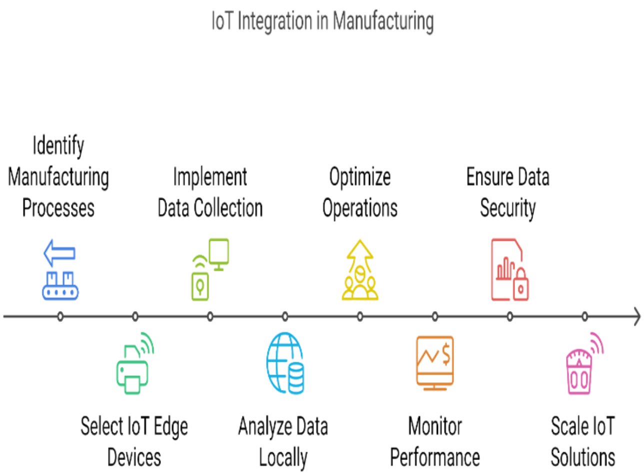
Table 1: Key Components of IoT in Manufacturing

Component	Description	Example Applications
Sensors	Devices that capture real-time data from machines, products, and environments.	Vibration, temperature, and humidity monitoring for predictive maintenance.
Actuators	Devices that respond to sensor data to perform specific actions or control machines.	Adjusting machine speed or stopping processes in case of anomalies.
Communication Protocols	Technologies that enable IoT devices to transmit data.	Wi-Fi is used for high-bandwidth data transmission, and Lo Ra WAN is used for long-range communication.
Edge Computing	Local processing of data to reduce latency and bandwidth usage.	Real-time analytics for machine performance monitoring.
Cloud Computing	Centralized data storage and advanced	Long-term data storage, large-scale machine

	analytics for IoT data.	learning models.
AI and ML	Algorithms that analyze IoT data for predictive maintenance and process optimization.	Predicting machine failures, optimizing production workflows.

2.4 Application of IoT Edge Computing in Smart Manufacturing

Edge computing acts as the nerve center for this transformation, bringing data processing closer to the source—right at the machinery and sensors on the shop floor. This proximity allows manufacturers to instantly process vast amounts of data, reducing latency and enabling immediate responses to fluctuating conditions. As industries grapple with increasing demands for customization and shorter production cycles, deploying edge computing solutions has emerged as a game-changer. It empowers manufacturers not only to enhance operational efficiency but also to innovate continuously in an era defined by relentless technological advancement. Whether it's predictive maintenance that prevents costly downtimes or adaptive systems that fine-tune processes in real-time, edge computing stands as a cornerstone technology propelling smart manufacturing into new frontiers of possibility.



Graph 2: Steps to enable IoT- Edge computing in Manufacturing

2.5 Challenges of IoT in Smart Manufacturing

Despite the benefits, IoT implementation in manufacturing faces several challenges:

1. **Data Security and Privacy:** IoT systems are vulnerable to cyberattacks, as they often involve large networks of devices with varying levels of security. Securing these networks from unauthorized access and data breaches is a significant concern.
2. **Interoperability:** Different IoT devices and platforms may use incompatible protocols or data formats, making it difficult to integrate systems across a manufacturing operation.
3. **Scalability:** As IoT systems grow in scale, managing large amounts of data and ensuring the reliable operation of thousands of devices become increasingly complex.

Cost: While IoT can lead to long-term savings, the initial investment in sensors, communication infrastructure, and cloud services can be high.

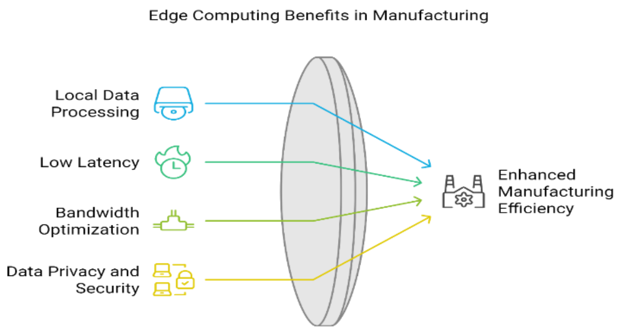
3.0 Edge Computing in Smart Manufacturing

3.1 Introduction to Edge Computing in Manufacturing

Edge computing is a decentralized data processing model that brings computation and data storage closer to the location where it is needed, often at or near the data source (e.g., sensors machines). In the context of smart manufacturing, edge computing plays a pivotal role in managing the massive amounts of data generated by Internet of Things (IoT) devices, enabling real-time processing and analysis. This is critical in manufacturing environments where low latency, high reliability, and fast decision-making are required to optimize processes and ensure smooth production.

The traditional cloud computing model involves transmitting data from IoT devices to remote data centers (cloud servers), where it is processed and analyzed. However, this model introduces latency due to the distance the data needs to travel, which can be problematic in time-sensitive manufacturing environments. Edge computing mitigates this issue by enabling data processing at the network's edge, closer to the IoT devices, reducing latency, and providing real-time insights.

Key Features of Edge Computing in Smart Manufacturing



Graph 3: Data collection for Manufacturing efficiency

1. **Local Data Processing:** Edge computing enables real-time data analysis and decision-making by processing data directly on edge devices or gateways. This is essential in scenarios requiring immediate responses, such as when a machine shows signs of failure and needs to be shut down or repaired to avoid disruptions.
2. **Low Latency:** The proximity of edge computing devices to the source of data significantly reduces the time it takes for data to be processed and actionable insights to be derived. This low latency is a significant advantage in manufacturing, where even milliseconds can impact production efficiency and quality.
3. **Bandwidth Optimization:** Edge computing reduces the burden on network bandwidth by processing data locally and only sending relevant or pre-processed data to the cloud. This is particularly important in manufacturing environments that generate vast amounts of data, as it prevents network congestion and reduces the cost of data transmission to the cloud.
4. **Data Privacy and Security:** Since data processing happens locally at the edge rather than in a remote cloud, sensitive manufacturing data can be kept within the factory, enhancing data privacy and security. This is especially important for manufacturers dealing with proprietary technologies or sensitive customer information.

3.2 Comparison with Traditional Cloud Computing

While cloud computing has been the dominant model for managing IoT data in manufacturing, it has several limitations when applied in real-time, mission-critical environments. One of the biggest challenges is latency: data sent to the cloud can take time to travel, be processed, and then return with insights or actions. This delay can disrupt processes that require instantaneous decisions, such as automated quality control systems or predictive maintenance that needs immediate action.

Edge computing addresses these challenges by bringing computation closer to the machines and sensors, enabling manufacturers to act on data faster and with higher reliability. For instance, instead of sending all sensor data from a production line to a remote cloud for analysis, edge devices can analyze the data locally and only send specific insights (such as alerts or anomalies) to the cloud, reducing both time and data load.

Applications of Edge Computing in Smart Manufacturing

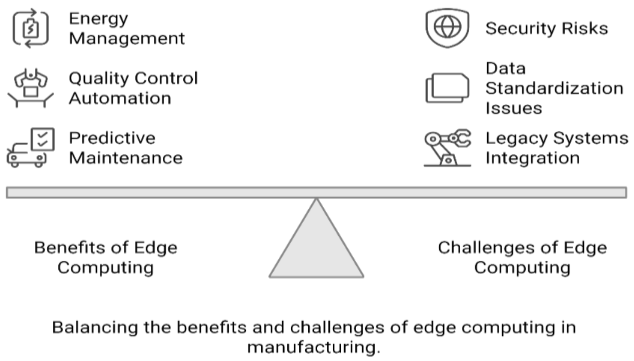
1. **Predictive Maintenance:** Manufacturing equipment is outfitted with IoT sensors that collect performance data. With edge computing, this data can be analyzed in real-time to detect anomalies, predict machine failures, and trigger maintenance actions before a breakdown occurs. This reduces downtime and extends the life of machinery.
2. **Automated Quality Control:** Quality control processes in smart manufacturing rely heavily on real-time data to detect product defects or inconsistencies. By analyzing data at the edge, manufacturers can instantly identify and correct defects on the production line, ensuring that faulty products are identified before they proceed further in the manufacturing process.
3. **Energy Management:** Edge computing allows for real-time energy consumption monitoring across the manufacturing facility. Energy usage data from machines

can be analyzed on-site to optimize energy use, reducing costs and contributing to more sustainable manufacturing practices.

4. **Autonomous Robotics and Vehicles:** In smart factories, autonomous robots and vehicles are used to transport materials, assemble products, and handle inventory. These systems require real-time processing to navigate and adapt to changing conditions in the factory. Edge computing ensures that these robots can process environmental data and make decisions locally without relying on the cloud, reducing latency and improving responsiveness.

Real-World Example of Edge Computing in Manufacturing Consider a smart manufacturing facility where IoT sensors monitor the health of machines, tracking data such as temperature, vibration, and pressure. An edge device analyzes this data in real-time, identifying signs of wear and tear. Suppose the data suggests a machine will likely fail within the next few hours. In that case, the edge device can trigger a maintenance alert and shut down the machine to prevent a breakdown without communicating with a remote cloud server. This quick action minimizes downtime and prevents costly repairs.

Another example can be found in automotive manufacturing, where assembly lines are equipped with cameras and sensors to inspect parts for defects. Instead of sending images to the cloud for analysis, edge devices analyze the images on-site, immediately flagging defects and preventing faulty parts from being used in the assembly process.



Graph 4: Benefits and challenges to overcome at Edge in Manufacturing.

Challenges of Implementing Edge Computing in Manufacturing Despite its advantages, edge computing comes with several challenges in smart manufacturing:

1. **Integration with Legacy Systems:** Many manufacturing facilities still rely on legacy systems and equipment that were not designed to connect to modern IoT networks or edge devices. Upgrading or retrofitting these systems can be costly and time-consuming.
2. **Data Standardization:** IoT devices and edge devices often come from different vendors, each using different protocols and standards for data communication. This lack of standardization can complicate the integration of edge computing into a manufacturing environment.
3. **Security Risks:** While edge computing can enhance data security by keeping sensitive information local, it also introduces new attack surfaces. Each edge device represents a potential vulnerability, and ensuring robust security at the edge is critical.
4. **Scalability:** Managing and maintaining many edge devices across a manufacturing facility can be challenging, particularly as the number of IoT devices grows. Developing scalable management systems that can handle updates, security patches, and device monitoring is essential for successfully implementing edge computing.

Future of Edge Computing in Smart Manufacturing

The future of edge computing in smart manufacturing is promising, especially with the development of complementary technologies such as 5G, artificial intelligence (AI), and machine learning (ML). The introduction of 5G networks will further reduce latency and increase the capacity of edge devices to process more data in real time, enabling more advanced use cases such as augmented reality (AR) for factory workers and AI-driven automation. Additionally, AI and ML algorithms will be increasingly deployed at the edge to enhance predictive analytics, optimize production processes, and enable autonomous decision-making.

4.IoT and Edge Computing Architecture for Smart Manufacturing

Integrating IoT (Internet of Things) and Edge Computing is a critical enabler of real-time data collection, processing, and decision-making in smart manufacturing. The architecture of IoT and Edge Computing in smart manufacturing is designed to leverage the strengths of both technologies, ensuring that manufacturing operations can run smoothly, efficiently, and with minimal downtime. Below is a detailed breakdown of how IoT and Edge Computing architecture operate in the context of smart manufacturing.

4.1 Overview of the Architecture

The IoT and Edge Computing architecture for smart manufacturing is structured to manage data flow from physical devices (such as sensors, machines, and other operational technology) to edge devices for processing and then potentially to the cloud for further analysis and storage. This system ensures that data is processed as close to the source as possible, which is critical for real-time decision-making and minimizing latency.

At a high level, the architecture includes:

- IoT Devices (Sensors and Actuators)
- Edge Computing Layer (Edge Devices and Gateways)
- Cloud Computing (Centralized Data Storage and Advanced Analytics)
- Communication Networks (Wired/Wireless Networks, 5G, Ethernet, etc.)

Each component in the architecture plays a specific role in ensuring seamless operation, from data collection to processing and optimization.

4.2 IoT Devices (Sensors and Actuators)

IoT devices form the foundation of smart manufacturing by connecting physical equipment and machinery to digital systems. These devices include:

- **Sensors:** Responsible for collecting data such as temperature, pressure, vibration, or speed from machines, equipment, and processes.
- **Actuators:** Devices that act based on the data collected by sensors, such as adjusting machine settings or stopping equipment to prevent damage.

The primary role of IoT devices in this architecture is to collect and transmit data to the edge devices. Data from sensors is continuous and voluminous, so it must be efficiently processed to enable real-time insights.

Example:

In a smart factory, sensors can detect an abnormal increase in temperature in a motor, which can lead to equipment failure. This data is transmitted to the edge for immediate processing and action.

4.3 Edge Computing Layer

Edge computing is the most important innovation in smart manufacturing because it allows data to be processed closer to where it is generated—on the factory floor rather than in a remote cloud environment. In this layer, edge devices (which are often referred to as gateways or edge servers) receive data from IoT sensors and process it locally before sending only the relevant or processed data to the cloud.

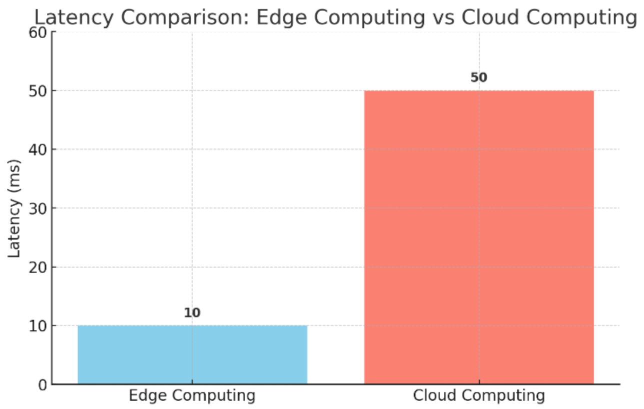
Key Functions of Edge Devices:

- **Local Data Processing:** Edge devices perform computations on data immediately as it is received, allowing for quick insights and action.
- **Filtering and Aggregation:** Edge computing systems can filter irrelevant data, reducing the volume of information sent to the cloud. For example, instead of sending every temperature reading to the cloud, only abnormal readings might be flagged and transmitted.
- **Low Latency Decision Making:** One of the critical advantages of edge computing is the reduction of latency, as decisions can be made on the spot without waiting for cloud-

based systems to respond. This is essential in time-sensitive manufacturing processes.

Example:

In the motor temperature example, the edge device might analyze the temperature data, compare it to predefined thresholds, and then automatically adjust machine settings or alert the maintenance team if necessary.



Graph 5: Edge Computing vs Cloud Computing Latency

4.4 Cloud Computing Layer

While edge computing handles local processing, cloud computing remains an essential part of the architecture for centralized data storage, large-scale data analytics, and long-term data retention. Data that requires more complex analysis, machine learning models, or integration with other systems is transmitted to the cloud.

Key Functions of Cloud Systems in this Architecture:

- **Centralized Data Analytics:** Cloud systems handle advanced analytics, including historical analysis, predictive maintenance, and integration with business intelligence platforms.
- **Machine Learning and AI Models:** Complex machine learning algorithms can be run in the cloud to develop predictive models, which can then be deployed back to the edge for real-time decision-making.
- **Scalability:** The cloud offers nearly infinite scalability for data storage and computing power, allowing smart factories to collect and analyze massive amounts of data.

Data Flow:

Data flows between the IoT devices and the cloud in a hierarchical structure. While edge computing handles real-time, low-latency decision-making, the cloud is responsible for deeper insights, longer-term trends, and advanced analytics.

4.5 Communication Networks

The communication network in this architecture is the backbone that links IoT devices, edge computing systems, and cloud platforms. Effective communication requires a combination of wired and wireless technologies to transmit data quickly and reliably.

Common Network Technologies:

- **Wired Networks (Ethernet):** Used for high-speed, reliable communication between machines and systems in fixed positions.
- **Wireless Networks (Wi-Fi, 5G):** Essential for mobile equipment, robots, and devices that are difficult to connect via wired systems.
- **Low-Power Wide Area Networks (LPWAN):** Technologies like LoRaWAN and NB-IoT are used for long-range communication between sensors and gateways, often in environments where power consumption is a concern.

The arrival of 5G, in particular, is seen as a game changer for smart manufacturing, offering ultra-low latency, high-speed data transfer, and greater reliability in connecting a vast number of IoT devices.

4.6 Real-World Example of IoT and Edge Computing Architecture

To better understand how this architecture is applied in real-world manufacturing, let's look at General Electric's (GE) implementation of edge computing in their smart factories. GE uses IoT sensors across its production lines to collect data in real time. The edge computing layer processes this data to detect any abnormalities in machine performance, allowing the system to make real-time adjustments.

For example, GE uses edge computing to monitor the performance of its turbines. Data on temperature, pressure, and vibration is collected by IoT sensors and processed at the edge, enabling immediate corrective actions if something goes wrong. This architecture helps reduce machine downtime, improve production quality, and optimize overall factory performance.

4.7 Advantages of IoT and Edge Computing Architecture in Smart Manufacturing

The architecture of IoT and Edge Computing offers several distinct advantages:

- **Real-time Data Processing:** The ability to process data locally allows for immediate responses to issues like equipment malfunctions.
- **Reduced Bandwidth Usage:** By processing data at the edge, only the most relevant data is sent to the cloud, reducing bandwidth consumption and network congestion.
- **Improved Security:** With less data being transmitted to the cloud, the risk of interception and cyberattacks is minimized.
- **Lower Latency:** Decision-making is faster because data is processed closer to the source, which is critical in manufacturing environments where milliseconds can matter.

5. Benefits of Combining IoT and Edge Computing in Smart Manufacturing

The integration of IoT (Internet of Things) and Edge Computing into smart manufacturing processes provides significant advantages by enabling real-time data processing, improving operational efficiency, and facilitating faster decision-making. Below are the detailed benefits of this combination:

5.1 Enhanced Decision-Making Speed

In traditional cloud-based systems, all data collected from IoT sensors must be transmitted to a centralized cloud server for processing and analysis. This process can introduce significant delays, especially when handling large volumes of data. Edge computing addresses this issue by processing data locally at the "edge" of the network, close to where it is generated (e.g., on factory floors or within production units).

By analyzing critical data locally, edge computing minimizes the latency associated with data transmission to the cloud, allowing manufacturers to make decisions in real-time. This speed is crucial in time-sensitive scenarios like detecting equipment malfunctions, managing production line issues, and adjusting to changes in operational conditions on the fly. For example:

- If an IoT sensor detects overheating in a machine, the local edge device can instantly shut down the system, preventing potential damage or downtime.

5.2 Reduced Latency and Improved Reliability

Edge computing eliminates the need for constant data transfer to the cloud by enabling local data processing. This significantly reduces latency—the time it takes for data to travel from the IoT device to the cloud and back. Reduced latency is particularly important in manufacturing, where delays can lead to production inefficiencies or equipment failures.

Moreover, local data processing provides improved reliability. Even in cases of network outages or connectivity issues, edge computing allows the factory floor to continue operating with local decision-making, ensuring that critical tasks are not interrupted. This local failover capability is critical for maintaining business continuity in manufacturing environments that require continuous operation.

5.3 Real-Time Monitoring and Predictive Maintenance

A combination of IoT and edge computing facilitates real-time monitoring of equipment and processes. IoT sensors deployed across a manufacturing facility collect data related to machine performance, environmental conditions, product quality, and more. By processing this data at the edge, manufacturers can instantly monitor their operations without waiting for cloud-based analytics.

In addition, edge computing enhances predictive maintenance strategies by processing machine data in real time and identifying potential failures before they occur. For instance, IoT sensors can monitor vibration levels, temperatures, and wear-and-tear data from machines. Edge devices use algorithms to analyze this data and detect patterns that indicate a need for maintenance. This predictive capability reduces unplanned downtime and maintenance costs while optimizing the use of resources.

- **Example:** A machine tool equipped with IoT sensors could detect abnormal vibrations. The edge device processing this data can immediately flag the issue and recommend maintenance before the tool breaks down, thereby preventing costly disruptions.

5.4 Energy Efficiency and Resource Optimization

By enabling real-time data processing and decision-making, IoT and edge computing allow manufacturers to optimize resource usage, leading to improved energy efficiency. Sensors embedded in equipment can monitor resource consumption, such as electricity, water, and raw materials. Based on this data, edge computing systems can make instantaneous adjustments to processes, ensuring optimal use of energy and other resources.

This approach not only reduces operational costs but also aligns with the growing trend toward sustainable manufacturing. For example, smart energy management systems powered by IoT and edge computing can automatically reduce the power usage of machines during off-peak production hours, minimizing energy waste.

- **Example:** A smart manufacturing facility can monitor and adjust energy consumption by shutting down non-essential machines during breaks, thereby lowering electricity usage.

5.5 Improved Data Privacy and Security

One of the major concerns with IoT-based systems is the transfer and storage of large amounts of sensitive data over the Internet. By processing data locally, edge computing reduces the need to send sensitive or critical data to the cloud, which enhances security. This local data processing ensures that only relevant, filtered data is sent to the cloud for long-term storage or advanced analytics, thereby limiting the exposure of sensitive information to potential cyber threats.

Additionally, edge devices can be equipped with security protocols such as encryption and authentication to protect data at the point of collection and processing. This reduces the attack surface for malicious actors and provides better control over data privacy, especially in industries with stringent regulatory requirements, like automotive or aerospace manufacturing.

5.6 Scalability and Flexibility

A significant advantage of combining IoT with edge computing is the ability to scale systems efficiently. In a manufacturing environment, thousands of IoT devices might generate massive amounts of data, overwhelming centralized cloud systems. With edge computing, data is processed locally, reducing the strain on cloud infrastructure. This localized processing allows manufacturers to easily scale up operations by adding new IoT devices without the need for significant investment in cloud-based data centers.

Edge computing also offers flexibility by allowing manufacturers to customize how data is processed, stored, and analyzed. Different manufacturing processes can be optimized based on their specific requirements, whether it be real-time analytics, reduced latency, or enhanced privacy.

5.7 Cost Efficiency

The combination of IoT and edge computing reduces operational costs in several ways:

- **Lower Bandwidth Costs:** Since data is processed locally at the edge, only relevant data is sent to the cloud, reducing bandwidth usage and associated costs.
- **Optimized Maintenance:** Predictive maintenance enabled by real-time data processing minimizes equipment failures

and reduces the costs of emergency repairs and unplanned downtime.

- **Energy Savings:** Edge computing's ability to optimize energy usage results in cost savings related to energy consumption and equipment wear.

By implementing IoT and edge computing, manufacturers can achieve long-term cost efficiency through better resource management, lower energy consumption, and reduced reliance on costly cloud infrastructure for real-time processing.

Summary of Benefits:

Benefit	**IoT Contribution**	**Edge Computing Contribution**
Reduced Latency	Real-time data collection	Local data processing
Improved Reliability	Constant monitoring	Local failover during connectivity issues
Predictive Maintenance	Continuous monitoring of machine health	Fast local analysis and action
Energy Efficiency	Monitor energy usage	Optimize energy consumption in real-time
Enhanced Security	Collect data from sensors	Process sensitive data locally, reducing exposure to threats

By combining IoT and edge computing, smart manufacturing facilities can benefit from faster decision-making, improved operational reliability, and enhanced cost efficiency while laying the foundation for future technological advancements such as AI-driven manufacturing and advanced predictive analytics.

6.0 Challenges and Limitations of IoT and Edge Computing in Smart Manufacturing

The integration of IoT and Edge Computing into smart manufacturing offers significant advantages. Still, it also presents several challenges and limitations that need to be addressed to harness the potential of these technologies fully. Below, we will explore the key challenges and constraints associated with IoT and Edge Computing in smart manufacturing, such as security, network infrastructure, data management, and scalability.

6.1 Security and Privacy Concerns

One of the most critical challenges in deploying IoT and edge computing in smart manufacturing is ensuring robust security and privacy. IoT devices often have limited computational power and storage, making it difficult to implement advanced security measures. With the vast amount of data collected and processed in real time, security risks such as cyberattacks, data breaches, and unauthorized access are heightened.

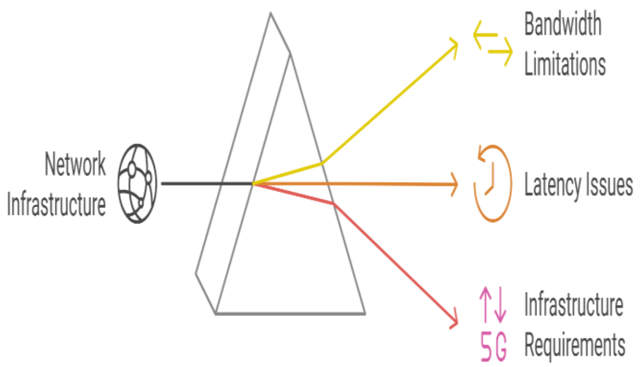
1. **Data Breaches and Cyberattacks:** IoT devices connected to the internet are vulnerable to attacks such as Distributed Denial of Service (DDoS), malware, and ransomware. Since IoT devices often communicate sensitive operational data, any breach could lead to disruptions in the manufacturing process, financial losses, and compromised intellectual property.
2. **Limited Security Protocols:** Many IoT devices in manufacturing lack advanced encryption protocols due to their low processing power. This makes it easier for attackers to intercept data or compromise devices. Edge computing partially mitigates this by processing data closer to the source, but robust end-to-end encryption across devices and networks is still necessary.
3. **Privacy Concerns:** In some cases, data collected from IoT devices may contain proprietary or personal information. Ensuring data privacy, particularly in compliance with regulations such as GDPR, is a significant challenge.

Mitigation Strategy: Implementing multi-layered security measures, including firewalls, intrusion detection systems (IDS), regular firmware updates, and device authentication protocols, can enhance IoT security in manufacturing environments.

Additionally, using encryption for data at rest and in transit is essential to protect sensitive information.

6.2 Network Infrastructure and Latency

A robust network infrastructure is vital for the effective deployment of IoT and edge computing. These technologies require fast, reliable, and low-latency networks, especially in manufacturing environments where downtime or delays can be costly.



Graph 6: Mitigate Latency with Infrastructure at Edge.

- **Bandwidth Limitations:** IoT devices generate large volumes of data that need to be transmitted to edge devices or cloud servers. Inadequate bandwidth can result in delayed or lost data transmission, which could affect real-time decision-making and process optimization.
- **Latency Issues:** One of the major reasons for adopting edge computing in manufacturing is to reduce latency by processing data close to the source. However, if the network infrastructure (such as 5G or fiber optic networks) is not well-developed, latency issues may persist, limiting the effectiveness of edge computing. High-latency environments can cause delays in automated decision-making, leading to inefficient production processes.
- **5G and Infrastructure Requirements:** While 5G technology promises ultra-low latency and high-speed communication, many manufacturing facilities, especially in remote areas, may not yet have access to 5G networks. The need to upgrade existing network infrastructure to support IoT and edge computing can be a significant challenge for manufacturers.

Mitigation Strategy: Manufacturers need to invest in scalable network solutions such as 5G or private wireless networks tailored to industrial environments. Edge computing can also be leveraged to reduce the dependency on cloud-based networks by handling critical data processing at local nodes.

6.3 Data Management and Integration

Managing the massive volumes of data generated by IoT devices in a smart manufacturing environment is a complex task. Edge computing helps alleviate some of this burden by processing data locally, but challenges remain in terms of data integration, storage, and real-time analysis.

- **Data Overload:** The sheer volume of data generated by sensors, machines, and other IoT devices can lead to data overload. Without proper management and analytics tools in place, manufacturers may struggle to extract meaningful insights from the data.
- **Data Integration and Interoperability:** IoT devices from different vendors may use various communication protocols, formats, and standards. Integrating this data into a cohesive system is challenging, especially when trying to achieve seamless communication between legacy systems and modern IoT-enabled devices.
- **Real-Time Data Processing:** Edge computing enables real-time data processing, but handling large-scale, high-frequency data streams at the edge still requires significant computational resources. If these resources are not optimized, it could lead to bottlenecks, affecting the efficiency of manufacturing processes.

Mitigation Strategy: Manufacturers should adopt advanced data management platforms that provide scalable storage, integration, and analytics capabilities. Investing in cloud-edge hybrid architectures that allow for real-time data processing at the edge and long-term storage in the cloud can also optimize data flow.

6.4 Scalability and Cost

Scaling IoT and edge computing solutions in smart manufacturing is another challenge. The initial investment required to install and maintain IoT devices, edge servers, and the supporting network infrastructure can be high, especially for small to medium-sized enterprises (SMEs).

- **Cost of Implementation:** Deploying IoT and edge devices requires substantial capital investment in hardware, software, and networking infrastructure. Furthermore, maintaining these devices (e.g., software updates, repairs, and security) adds ongoing operational costs.
- **Scalability Challenges:** As manufacturers seek to expand their IoT and edge computing systems to cover more equipment or processes, scalability becomes a concern. More devices mean more data, and ensuring that the network infrastructure, edge servers, and cloud systems can scale to handle this increase in data is essential.

Mitigation Strategy: Adopting a phased implementation approach can help mitigate costs. Start by deploying IoT and edge computing in critical areas of manufacturing and gradually expand as the benefits become evident. Leveraging cloud-edge hybrid models can also help control costs while providing the flexibility to scale up or down as needed.

6.5 Data Standardization and Interoperability

IoT and edge computing involve various devices, platforms, and technologies, often from different manufacturers. Ensuring these systems can work together seamlessly is a challenge, especially when considering the different data formats, communication protocols, and standards used by various devices.

- **Lack of Universal Standards:** The lack of universal standards in IoT and edge computing creates difficulties when trying to integrate devices from different vendors. This can result in compatibility issues, where devices cannot communicate effectively with each other or with central systems.
- **Interoperability Issues:** Smart manufacturing environments often include a mix of legacy systems and newer IoT-enabled devices. Ensuring that these disparate systems can interoperate smoothly is a major challenge, particularly when trying to collect, analyze, and act on data from various sources.

Mitigation Strategy: Manufacturers can adopt open standards and protocols that promote interoperability, such as MQTT, OPC UA, and others. Collaborating with vendors that support cross-platform integration and future-proofing systems through modular architectures can reduce interoperability challenges.

6.6 Edge Device Management and Maintenance

Managing a large fleet of edge devices in a smart manufacturing environment can be complex, especially since these devices are located closer to the factory floor and require regular maintenance and updates.

1. **Device Monitoring and Maintenance:** Edge devices need continuous monitoring for performance, security, and fault detection. Managing a large number of edge nodes, especially in geographically distributed locations, can be resource-intensive.
2. **Firmware and Software Updates:** Regular updates to firmware and software are necessary to ensure security and functionality. However, updating these devices at scale can be challenging, particularly if they are located in remote or hard-to-access areas.

Mitigation Strategy: Implementing a centralized management system for edge devices that automates monitoring, maintenance, and updates can streamline operations. Cloud-based management platforms can provide real-time visibility into the health and status of edge devices, ensuring they operate efficiently with minimal downtime.

While IoT and Edge Computing have the potential to revolutionize smart manufacturing, overcoming these challenges is crucial for manufacturers to leverage the benefits of these technologies fully. By addressing security concerns, building scalable and robust network infrastructures, and optimizing data management and device maintenance, manufacturers can create more resilient and efficient smart factories.

7.Future Trends in IoT and Edge Computing for Smart Manufacturing

The convergence of IoT and edge computing is set to revolutionize smart manufacturing by driving efficiency, productivity, and innovation. As technology continues to evolve, several trends are expected to shape the future landscape of IoT and edge computing in manufacturing environments. This section explores these trends and their implications.

7.1 5G Integration

The rollout of 5G technology is one of the most significant advancements impacting IoT and edge computing in smart manufacturing. With its ultra-low latency, higher bandwidth, and increased device connectivity, 5G will enable real-time data transmission and communication between machines, sensors, and systems.

Implications:

1. **Enhanced Real-Time Monitoring:** Manufacturers can utilize 5G to connect a vast number of devices without latency issues, allowing for instantaneous data collection and analysis.
2. **Increased Automation:** With reliable and fast connections, manufacturers can deploy more autonomous systems and robots that can communicate and make decisions in real-time.
3. **Support for Advanced Applications:** Technologies such as augmented reality (AR) and virtual reality (VR) will benefit from 5G, enabling immersive training experiences and remote assistance.

7.2 AI and ML at the Edge

Artificial Intelligence (AI) and Machine Learning (ML) are set to play crucial roles in the evolution of edge computing for smart manufacturing. By processing data closer to the source, edge devices can leverage AI and ML algorithms to gain insights and optimize operations in real time.

Implications:

1. **Predictive Maintenance:** AI-driven analytics can predict equipment failures before they occur by analyzing historical and real-time data, significantly reducing downtime and maintenance costs.
2. **Process Optimization:** Machine learning algorithms can analyze production processes and identify inefficiencies, allowing for adjustments to be made dynamically, enhancing overall operational efficiency.
3. **Enhanced Quality Control:** AI can improve quality assurance processes by analyzing product data in real-time, identifying defects faster, and enabling immediate corrective actions.

7.3 Digital Twins

The concept of digital twins—virtual replicas of physical systems—has gained traction in smart manufacturing. Digital twins enable real-time simulations of processes, equipment, and systems, allowing manufacturers to analyze performance and predict outcomes.

Implications:

- **Improved Decision-Making:** By simulating different scenarios, manufacturers can make informed decisions regarding production planning, resource allocation, and risk management.
- **Optimized Asset Management:** Digital twins can facilitate better asset tracking and management, helping manufacturers maximize the lifespan and efficiency of their equipment.

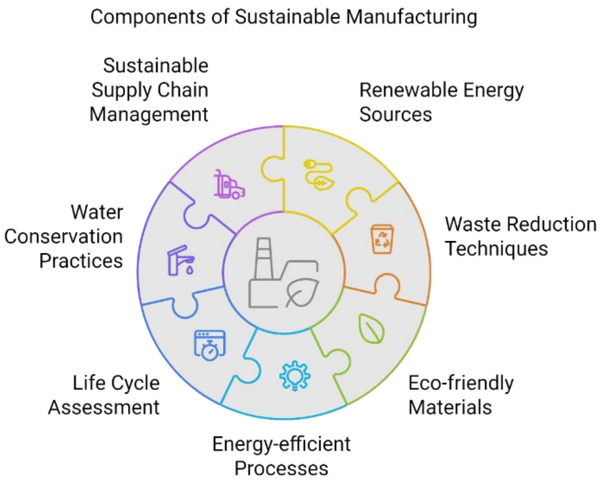
- **Enhanced R&D:** Digital twins provide a platform for testing new processes and products in a risk-free environment, accelerating innovation and reducing time-to-market.

7.4 Sustainability and Green Manufacturing

As industries face increasing pressure to adopt sustainable practices, IoT and edge computing are poised to contribute significantly to green manufacturing initiatives. By improving efficiency and reducing waste, these technologies can help manufacturers meet their sustainability goals.

Implications:

- **Energy Efficiency:** IoT sensors can monitor energy consumption in real time, identifying areas for improvement and enabling energy-saving measures to be implemented quickly.
- **Waste Reduction:** Real-time data analysis can help manufacturers minimize material waste by optimizing production processes and supply chain management.
- **Sustainable Supply Chains:** IoT can enhance transparency in supply chains, allowing manufacturers to source materials sustainably and reduce their environmental footprint.



Graph 7: Value chain of sustainability in Manufacturing.

7.5 Enhanced Cybersecurity Measures

As the number of connected devices increases, so does the risk of cyber threats. Future trends in IoT and edge computing will likely focus on enhancing cybersecurity measures to protect sensitive data and manufacturing systems.

Implications:

- **Decentralized Security Approaches:** Edge computing allows for localized security protocols, enabling faster response times to threats and minimizing the risk of data breaches.
- **AI-Driven Threat Detection:** Advanced AI algorithms can identify and mitigate security threats in real time, safeguarding manufacturing environments from cyber-attacks.
- **Regulatory Compliance:** As data protection regulations evolve, manufacturers will need to implement robust security frameworks to comply with standards and ensure data integrity.

7.6 Integration with Blockchain Technology

Blockchain technology is gaining attention for its potential to enhance data integrity and security in IoT applications. In smart manufacturing, blockchain can provide a decentralized and tamper-proof ledger for tracking transactions, inventory, and product lifecycle.

Implications:

- **Improved Traceability:** Blockchain can enhance the traceability of products from raw materials to end-users, enabling manufacturers to address quality issues quickly and recalls.
- **Secure Data Sharing:** Manufacturers can securely share data with suppliers and partners through blockchain, enhancing collaboration while protecting sensitive information.
- **Smart Contracts:** Automating contractual agreements through smart contracts can streamline processes such as payments, inventory management, and logistics, improving operational efficiency.

Table 3: Future Trends in IoT and Edge Computing for Manufacturing

Trend	Description	Potential Impact on Manufacturing
5G Integration	Ultra-low latency, faster data speeds	Real-time remote monitoring
AI and ML at the Edge	Enhanced predictive analytics at the edge	Reduced downtime, increased efficiency
Digital Twins	Real-time digital simulations of physical systems	Improved monitoring and control

The integration of IoT and edge computing in smart manufacturing is driving a new era of innovation, efficiency, and sustainability. As these technologies continue to evolve, the trends outlined in this section will shape the future of manufacturing, enabling organizations to remain competitive in an increasingly digital landscape. By embracing these trends, manufacturers can harness the full potential of IoT and edge computing to optimize operations, enhance decision-making, and meet the demands of a rapidly changing market.

8. Conclusion

The integration of IoT and Edge Computing represents a significant evolution in the landscape of smart manufacturing, positioning it at the forefront of the fourth industrial revolution, also known as Industry 4.0. This research has highlighted the transformative potential of these technologies, demonstrating how they can enhance operational efficiency, improve decision-making processes, and enable real-time monitoring and analytics across manufacturing environments.

The key findings of this paper indicate that IoT provides manufacturers with the ability to gather and analyze vast amounts of data from various sensors and devices in real-time. This connectivity facilitates predictive maintenance, enhances supply chain visibility, and enables more responsive manufacturing processes. By leveraging IoT, manufacturers can not only optimize their operations but also significantly reduce costs associated with downtime and inefficiencies.

Edge Computing complements IoT by addressing the challenges associated with latency and bandwidth limitations inherent in traditional cloud computing models. By processing data closer to the source, edge computing ensures that manufacturers can make timely decisions based on up-to-date information, leading to faster responses to operational challenges. The combination of these technologies mitigates the risks associated with data transmission, particularly in scenarios where immediate action is critical.

Despite the numerous benefits, the deployment of IoT and edge computing in manufacturing is not without its challenges. Security remains a paramount concern, with increased connectivity exposing systems to potential cyber threats. Additionally, the need for robust network infrastructure, particularly with the rollout of 5G technology, is essential to support the extensive data requirements of IoT and edge solutions. Standardization and interoperability across diverse devices also pose significant hurdles that manufacturers must navigate to realize the full potential of these technologies.

Looking ahead, the future of smart manufacturing is poised for remarkable advancements driven by ongoing developments in IoT and edge computing. The integration of Artificial Intelligence (AI) and Machine Learning (ML) into edge computing frameworks will further enhance predictive analytics capabilities, enabling manufacturers to address issues before they escalate preemptively. Moreover, the adoption of digital twins will facilitate real-time monitoring and simulation of manufacturing processes, leading to even greater efficiencies.

Sustainability is another critical factor that will shape the future of smart manufacturing. As manufacturers increasingly focus on reducing their environmental footprint, IoT and edge computing can play pivotal roles in optimizing energy usage, minimizing waste, and enhancing resource management.

In conclusion, the convergence of IoT and Edge Computing is redefining the manufacturing sector, offering unprecedented opportunities for innovation and efficiency. By embracing these technologies, manufacturers can not only enhance their competitive edge but also contribute to a more sustainable and responsive industrial ecosystem. The journey toward fully realized smart manufacturing is ongoing, and organizations that proactively address the associated challenges will be best positioned to thrive in this dynamic landscape.

References

1. Nain, G., Pattanaik, K. K., & Sharma, G. K. (2022). Towards edge computing in intelligent manufacturing: Past, present and future. Journal of Manufacturing Systems, 62, 588-611.
2. Qi, Q., & Tao, F. (2019). A smart manufacturing service system based on edge computing, fog computing, and cloud computing. IEEE Access, 7, 86769-86777.
3. Carvalho, G., Cabral, B., Pereira, V., & Bernardino, J. (2021). Edge computing: current trends, research challenges, and future directions. Computing, 103(5), 993-1023.
4. Qiu, T., Chi, J., Zhou, X., Ning, Z., Atiquzzaman, M., & Wu, D. O. (2020). Edge computing in industrial internet of things: Architecture, advances and challenges. IEEE Communications Surveys & Tutorials, 22(4), 2462-2488.
5. Qu, Y. J., Ming, X. G., Liu, Z. W., Zhang, X. Y., & Hou, Z. T. (2019). Smart manufacturing systems: state of the art and future trends. The International Journal of Advanced Manufacturing Technology, 103, 3751-3768.
6. Mourtzis, D., Angelopoulos, J., & Panopoulos, N. (2021). Smart manufacturing and tactile internet based on 5G in industry 4.0: Challenges, applications and new trends. Electronics, 10(24), 3175.
7. Pan, J., & McElhannon, J. (2017). Future edge cloud and edge computing for internet of things applications. IEEE Internet of Things Journal, 5(1), 439-449.
8. Kubiak, K., Dec, G., & Stadnicka, D. (2022). Possible applications of edge computing in the manufacturing industry—systematic literature review. Sensors, 22(7), 2445.
9. Cheng, J., Chen, W., Tao, F., & Lin, C. L. (2018). Industrial IoT in 5G environment towards smart manufacturing. Journal of Industrial Information Integration, 10, 10-19.
10. Hamdan, S., Ayyash, M., & Almajali, S. (2020). Edge-computing architectures for internet of things applications: A survey. Sensors, 20(22), 6441.
11. Yang, H., Kumara, S., Bukkapatnam, S. T., & Tsung, F. (2019). The internet of things for smart manufacturing: A review. IISE transactions, 51(11), 1190-1216.
12. Kausar, M., Ishtiaq, M., & Hussain, S. (2021). Distributed agile patterns-using agile practices to solve offshore development issues. IEEE Access, 10, 8840-8854.
13. Kausar, M., & Al-Yasiri, A. (2015, July). Distributed agile patterns for offshore software development. In 12th International Joint Conference on Computer Science and Software Engineering (JCSSE), IEEE (p. 17).
14. Kausar, M., Muhammad, A. W., Jabbar, R., & Ishtiaq, M. (2022). Key challenges of requirement change management in the context of global software development: systematic literature review. Pakistan Journal of Engineering and Applied Sciences.
15. Vaithianathan, M. (2024). Real-Time Object Detection and Recognition in FPGA-Based Autonomous Driving Systems. International Journal of Computer Trends and Technology, 72(4), 145-152.

16. Kausar, M., & Al-Yasiri, A. (2017). Using distributed agile patterns for supporting the requirements engineering process. Requirements Engineering for Service and Cloud Computing, 291-316. Cena, J., & Harry, A. (2024). Blockchain-Based Solutions for Privacy-Preserving Authentication and Authorization in Networks.
17. Vaithianathan, M., Patil, M., Ng, S. F., & Udkar, S. (2023). Comparative Study of FPGA and GPU for High-Performance Computing and AI. ESP International Journal of Advancements in Computational Technology (ESP-IJACT), 1(1), 37-46.
18. Kausar, M., Mazhar, N., Ishtiaq, M., & Alabrah, A. (2023). Decision Making of Agile Patterns in Offshore Software Development Outsourcing: A Fuzzy Logic-Based Analysis. Axioms, 12(3), 307.
19. Vaithianathan, M., Patil, M., Ng, S. F., & Udkar, S. (2024). Integrating AI and Machine Learning with UVM in Semiconductor Design. ESP International Journal of Advancements in Computational Technology (ESP-IJACT) Volume, 2, 37-51.
20. Kausar, M. (2018). Distributed agile patterns: an approach to facilitate agile adoption in offshore software development. University of Salford (United Kingdom).
21. Seenivasan, D., & Vaithianathan, M. Real-Time Adaptation: Change Data Capture in Modern Computer Architecture.
22. Mazhar, N., & Kausar, M. (2023). Rational Coordination in Cognitive Agents: A Decision-Theoretic Approach Using ERMM. IEEE Access.
23. Wang, J. (2021). Impact of mobile payment on e-commerce operations in different business scenarios under cloud computing environment. International Journal of System Assurance Engineering and Management, 12(4), 776-789.
24. Wang, J., & Zheng, G. (2020). Research on E-commerce Talents Training in Higher Vocational Education under New Business Background. INTI JOURNAL, 2020(5).
25. Xiao, G., Lin, Y., Lin, H., Dai, M., Chen, L., Jiang, X., ... & Zhang, W. (2022). Bioinspired self-assembled Fe/Cu-phenolic building blocks of hierarchical porous biomass-derived carbon aerogels for enhanced electrocatalytic oxygen reduction. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 648, 128932.
26. Xiao, G., Lin, H., Lin, Y., Chen, L., Jiang, X., Cao, X., ... & Zhang, W. (2022). Self-assembled hierarchical metal–polyphenol-coordinated hybrid 2D Co–C TA@ gC 3 N 4 heterostructured nanosheets for efficient electrocatalytic oxygen reduction. Catalysis Science & Technology, 12(14), 4653-4661.