



EDGE COMPUTING FOR REAL-TIME DECISION-MAKING IN INDUSTRIAL INFORMATION SYSTEMS

Dr. Asad Rehman ¹

Abstract. *Edge computing has emerged as a transformative technology for enhancing real-time decision-making in industrial information systems. By bringing computational resources closer to data sources, edge computing significantly reduces latency, increases efficiency, and supports autonomous decision-making processes. This paper explores the role of edge computing in industrial environments, focusing on its applications, benefits, and challenges. The integration of edge computing with Industrial Internet of Things (IIoT) devices is investigated, highlighting how real-time data processing enhances operational performance. Key industries, including manufacturing, logistics, and healthcare, are examined to showcase the practical implications of edge computing for decision support systems. Through the analysis of various case studies and existing literature, the paper provides an overview of current trends and outlines the future potential of edge computing in industrial applications.*

Keywords: *Edge Computing, Real-Time Decision-Making, Industrial Information Systems, Industrial Internet of Things (IIoT).*

INTRODUCTION

Edge computing has revolutionized the way data is processed and analyzed in industrial settings. With the increasing use of connected devices and sensors, the need for real-time data processing has never been more critical. Traditional cloud computing models often introduce delays due to the distance between data sources and centralized processing units. Edge computing addresses this challenge by performing computations closer to the source of data, leading to faster decision-making and improved system responsiveness.

In the context of industrial information systems, edge computing facilitates real-time analytics, ensuring that industries can react to changing conditions swiftly. For example, in manufacturing environments, edge computing can process sensor data from machinery in real time to predict equipment failures before they happen. Similarly, in logistics, real-time tracking of goods enables immediate adjustments to delivery routes, enhancing operational efficiency.

¹ *Department of Computer Science, COMSATS University Islamabad, Pakistan.*

This paper aims to explore the application of edge computing in real-time decision-making for industrial systems, focusing on its integration with IIoT, benefits, challenges, and the future of this technology.

1. OVERVIEW OF EDGE COMPUTING

Definition and Key Concepts:

Edge computing refers to the practice of processing data closer to the data source, rather than relying on centralized cloud computing infrastructure. This decentralized approach minimizes latency, reduces bandwidth usage, and enables faster decision-making by allowing computations to occur locally at or near the edge of the network. Key concepts within edge computing include local processing, real-time data analytics, and distributed architectures. It often involves edge devices such as sensors, gateways, and industrial machines that collect and analyze data in real time.

Differences between Cloud Computing and Edge Computing:

- **Location of Data Processing:**
 - **Cloud Computing:** Data is processed in centralized data centers, often far from the point of data collection. This can lead to higher latency, especially in time-sensitive applications.
 - **Edge Computing:** Data is processed at or near the source of generation (edge of the network), reducing latency and improving real-time decision-making capabilities.
- **Data Transfer and Bandwidth:**
 - **Cloud Computing:** Large amounts of data must be sent over the internet to centralized servers, consuming significant bandwidth.
 - **Edge Computing:** Only relevant or processed data is transmitted, reducing the amount of bandwidth required and enabling quicker responses.
- **Latency:**
 - **Cloud Computing:** Typically suffers from higher latency due to long distances between data sources and data centers.
 - **Edge Computing:** Reduced latency as processing occurs locally or at nearby edge devices, allowing for faster decision-making.
- **Scalability:**
 - **Cloud Computing:** Highly scalable due to centralized infrastructure but may face challenges in handling real-time demands.
 - **Edge Computing:** Scales by distributing computing across multiple devices at the edge of the network.

Evolution and Growth of Edge Computing in Industrial Settings:

The rise of edge computing in industrial settings coincided with the growth of the Industrial Internet of Things (IIoT). In traditional manufacturing systems, data was collected but often not analyzed in real time, resulting in slow or reactive decision-making. With the advent of connected devices, sensors, and smart machines, edge computing has enabled industries to process data locally and make decisions in real time.

Initially, edge computing was more focused on IT-centric applications, but over time it has expanded into critical industrial domains such as predictive maintenance, real-time quality control, and automation systems. As industries demand higher efficiency and reduced downtime,

edge computing has become essential for enabling intelligent systems that can react to operational changes instantly. Today, industries such as manufacturing, logistics, and healthcare increasingly rely on edge computing to drive efficiency, innovation, and operational success.

2. INDUSTRIAL INFORMATION SYSTEMS AND REAL-TIME DECISION-MAKING

Importance of Real-Time Data Processing in Industries:

Real-time data processing is crucial in industrial environments where decisions need to be made rapidly to ensure operational continuity and safety. For instance, in manufacturing, real-time data from production lines can identify anomalies or equipment failures immediately, allowing corrective actions to be taken before a failure disrupts the entire process. In logistics, real-time data from GPS and sensors can optimize delivery routes dynamically, reducing fuel costs and improving customer satisfaction.

Industries are becoming more reliant on real-time data analytics to gain a competitive edge. The speed and accuracy with which data can be processed at the edge of the network significantly enhance operational decision-making, leading to improved production efficiency, better resource allocation, and higher customer satisfaction.

The Role of Industrial Information Systems in Improving Decision-Making Processes:

Industrial information systems (IIS) consist of the technologies and tools used to collect, store, analyze, and interpret data generated by industrial equipment. These systems provide decision-makers with critical insights into operational performance, resource utilization, and potential risks. In industries such as manufacturing, energy, and logistics, real-time data gathered through IoT devices and sensors is analyzed by IIS to support informed decision-making.

The integration of edge computing with IIS enables industries to make decisions instantly based on the most up-to-date information, thus enhancing operational responsiveness. For example, predictive maintenance systems powered by real-time data from machinery can trigger automatic repairs or alerts, reducing downtime and preventing costly breakdowns.

Challenges Faced by Traditional Systems in Managing Large Volumes of Data:

Traditional industrial information systems often struggle with the management of large volumes of data due to their reliance on centralized computing models. These systems typically rely on cloud or on-premises data centers to process and store data, leading to significant delays in decision-making due to the time it takes to transfer vast amounts of data to a central server.

Other challenges include:

- **Latency Issues:** Delays in processing and decision-making due to the centralized nature of traditional systems.
- **Bandwidth Limitations:** The high cost and inefficiency of transferring large volumes of raw data to centralized servers for analysis.

- **Security and Privacy Concerns:** Centralized data storage can become vulnerability, increasing the risk of cyberattacks and data breaches.

Edge computing addresses these challenges by enabling decentralized processing and reducing the need to send large volumes of data over networks, leading to faster decision-making and more secure, efficient systems.

3. THE INTEGRATION OF EDGE COMPUTING WITH IIOT

Overview of IIoT and Its Relevance to Edge Computing:

The Industrial Internet of Things (IIoT) refers to the interconnected network of industrial devices, machines, sensors, and software that collect, exchange, and analyze data in real time. IIoT has transformed industrial sectors by enabling smarter automation, predictive maintenance, and more efficient operations. However, to fully leverage the potential of IIoT, real-time data processing capabilities are essential, which is where edge computing plays a critical role.

Edge computing brings computational power closer to IIoT devices, allowing them to process data locally instead of sending it to remote cloud servers. This reduces latency, ensures quicker decision-making, and improves the efficiency of IIoT systems. By providing real-time analytics at the edge, industries can monitor their operations continuously, detect anomalies, and make informed decisions without delay.

How Edge Computing Enhances IIoT Functionalities:

Edge computing enhances IIoT by:

- **Reducing Latency:** By processing data at the source, edge computing minimizes the delay typically encountered when data is sent to distant cloud servers, enabling near-instantaneous responses.
- **Improving Bandwidth Efficiency:** Edge computing processes data locally and only transmits relevant information, reducing the strain on bandwidth and minimizing data transmission costs.
- **Increasing Reliability:** Edge computing ensures that even if the connection to the cloud is interrupted, local devices can continue processing and decision-making, which is crucial for critical applications in industries like manufacturing and healthcare.
- **Supporting Autonomous Systems:** Edge computing enables real-time processing and decision-making, which is essential for autonomous systems, such as robotic arms, automated vehicles, and drones.

Case Studies of IIoT Systems Leveraging Edge Computing for Real-Time Analytics:

1. **Predictive Maintenance in Manufacturing:** An automotive manufacturing facility equipped with sensors and IIoT devices for monitoring machinery health uses edge computing to detect anomalies in real time. Edge devices analyze vibration data from machines to predict failures before they happen, allowing the system to schedule maintenance automatically, minimizing downtime and reducing maintenance costs.
2. **Smart Grids in Energy Management:** A smart grid system in a power plant utilizes edge computing to monitor real-time energy consumption and demand. Edge devices process data locally from smart meters and control devices, adjusting the flow of electricity to optimize

energy distribution without waiting for cloud-based processing. This reduces energy wastage and ensures grid stability.

3. **Logistics and Fleet Management:** A logistics company implements edge computing on its fleet of delivery trucks. Each truck is equipped with IoT sensors that collect data on fuel usage, speed, and location. Edge devices process this data in real time, enabling the company to optimize routes dynamically, reduce fuel consumption, and ensure timely deliveries.

These case studies demonstrate how edge computing can be integrated into IIoT systems to provide real-time analytics and improve decision-making across various industries.

4. APPLICATIONS OF EDGE COMPUTING IN INDUSTRY

Manufacturing and Predictive Maintenance:

In manufacturing, edge computing plays a pivotal role in improving efficiency and reducing downtime. By placing computational power at the edge of the network, close to the manufacturing machines and equipment, it allows for real-time data processing and analytics. For predictive maintenance, edge devices collect data from various sensors embedded in machinery to monitor parameters like vibration, temperature, and pressure. This data is processed locally, enabling the detection of anomalies and the prediction of potential failures before they occur.

For example, in an automotive assembly plant, edge computing can analyze vibration patterns from robotic arms and machine tools in real time. If any unusual pattern is detected, the system can send immediate alerts to maintenance teams, preventing costly breakdowns and production delays. Predictive maintenance not only ensures continuous production but also helps in optimizing the lifecycle of expensive equipment.

Logistics and Real-Time Tracking:

In logistics, edge computing enhances operational efficiency by providing real-time tracking and monitoring of goods, vehicles, and shipments. Sensors placed on delivery trucks, packages, and warehouse shelves generate a vast amount of data, such as GPS location, temperature, humidity, and movement. By processing this data at the edge, logistics companies can track shipments, manage inventory, and adjust delivery routes in real time.

For instance, a shipping company could use edge computing to monitor the temperature of refrigerated containers in transit. If the temperature deviates from the desired range, the edge system can immediately alert the driver or warehouse staff to make adjustments. Similarly, the system can dynamically reroute vehicles based on traffic conditions, weather changes, or customer requirements, improving delivery times and reducing costs.

Healthcare and Patient Monitoring Systems:

Edge computing also finds applications in healthcare, particularly in-patient monitoring systems where real-time data is critical. Medical devices, such as wearables, smart sensors, and diagnostic equipment, continuously generate data on patient health, including heart rate, blood pressure, oxygen levels, and more. Edge computing enables the processing of this data locally, allowing for faster and more accurate medical assessments.

For example, in an intensive care unit (ICU), edge computing can analyze patient vitals in real time and trigger alarms if any values cross critical thresholds. This immediate response capability allows healthcare providers to act swiftly, improving patient outcomes. Additionally, edge computing can support telemedicine applications by enabling real-time diagnostics in remote areas, where low-latency communication is crucial for accurate decision-making.

Energy Management and Smart Grids:

Energy management and smart grids benefit significantly from edge computing by enabling real-time monitoring, control, and optimization of power distribution. Smart grids use sensors and smart meters to gather data on energy consumption, voltage levels, and grid stability. Edge computing can analyze this data in real time and make immediate decisions on energy distribution, load balancing, and fault detection.

For instance, edge computing can help detect and isolate faults in the grid by processing sensor data from various points within the network. If an anomaly is detected, the system can automatically reroute power to prevent blackouts or brownouts. Moreover, edge computing can enhance energy efficiency by enabling dynamic pricing and optimizing power usage based on real-time demand, contributing to cost savings and sustainability efforts.

5. BENEFITS OF EDGE COMPUTING FOR REAL-TIME DECISION-MAKING

Reduced Latency and Faster Response Times:

One of the key advantages of edge computing is the reduction in latency. By processing data at the edge of the network, closer to the source of data generation, it eliminates the delays associated with sending data to centralized cloud servers. This low-latency processing is essential in time-critical applications such as autonomous vehicles, industrial automation, and healthcare monitoring systems. Faster response times improve decision-making capabilities, enabling immediate action based on real-time information.

For example, in an industrial automation setup, edge computing can analyze sensor data from production lines to detect defects or irregularities in the manufacturing process. This allows operators to intervene quickly and prevent defective products from reaching customers, thus improving product quality and reducing waste.

Enhanced Operational Efficiency and Cost Savings:

Edge computing enables industries to optimize operations by reducing the need for centralized cloud computing resources and minimizing data transfer costs. By processing data locally, industries can reduce bandwidth consumption, lower cloud storage costs, and avoid network congestion. Real-time analytics provided by edge devices can also improve operational decision-making, resulting in cost savings.

For instance, in manufacturing, predictive maintenance powered by edge computing reduces unplanned downtime and lowers maintenance costs. In logistics, real-time route optimization through edge computing can reduce fuel costs and improve delivery efficiency. These operational efficiencies translate into substantial cost savings over time.

Improved Scalability and Flexibility:

Edge computing offers scalable solutions that can easily adapt to changing business needs. By adding more edge devices or nodes to the network, industries can increase their computational capacity without overloading centralized cloud infrastructure. Edge computing's decentralized nature also provides flexibility in deployment, allowing companies to scale their operations based on regional needs or specific business functions.

In industries like agriculture, edge computing can be used to scale smart farming solutions. For example, additional sensors can be added to monitor soil conditions, water usage, or crop health in different areas of a farm. The decentralized processing of data allows these solutions to be customized for various regions and crop types, providing flexibility and adaptability.

Increased Data Security and Privacy:

Edge computing improves data security and privacy by keeping sensitive data local, rather than transmitting it to distant cloud servers. This reduces the risks associated with data breaches and unauthorized access during data transmission. In industries such as healthcare and finance, where privacy is paramount, edge computing ensures that personal and sensitive data remains protected.

For example, patient health data collected by wearables or in-hospital devices can be processed locally on edge devices without needing to send it to a cloud server. This not only speeds up the analysis but also minimizes the exposure of sensitive data to potential cyber threats. In financial services, edge computing can process transactions and data locally to prevent unauthorized access to banking information.

6. CHALLENGES AND BARRIERS TO EDGE COMPUTING ADOPTION

Technical and Infrastructure-Related Challenges:

While edge computing offers numerous benefits, its adoption is not without challenges. The primary technical hurdle is the integration of edge devices into existing infrastructure. Many legacy systems may not be compatible with edge computing solutions, requiring substantial upgrades or redesigns. Additionally, the management of a distributed network of edge devices can be complex, as it requires robust monitoring and maintenance tools to ensure the reliability and performance of the system.

The infrastructure needed to support edge computing is also a barrier. Industrial environments often lack the necessary hardware, such as high-performance edge servers or IoT devices, and establishing these systems can be costly. Moreover, the deployment of edge computing across multiple locations can lead to management challenges related to system coordination, data synchronization, and network connectivity.

Data Privacy and Security Concerns:

As edge computing involves the processing of sensitive data locally, data privacy and security concerns remain significant barriers to adoption. Edge devices, being distributed across multiple locations, are more vulnerable to physical and cyberattacks compared to centralized cloud infrastructure. Securing these devices and the data they handle requires advanced encryption techniques and the implementation of robust access control mechanisms.

Industries such as healthcare and finance are particularly concerned about the security implications of storing and processing sensitive data at the edge. Ensuring compliance with regulations such as GDPR (General Data Protection Regulation) and HIPAA (Health Insurance Portability and Accountability Act) is a major concern for organizations looking to implement edge computing solutions.

High Initial Setup Costs:

The initial cost of deploying edge computing systems can be high due to the need for specialized hardware, software, and infrastructure. Edge devices and servers are often expensive, and companies may need to invest in additional networking equipment to ensure seamless communication between edge devices and centralized cloud servers.

In industries with tight budgets or limited resources, the cost of implementing edge computing solutions can be a significant barrier. While the long-term benefits of reduced latency, improved efficiency, and cost savings are clear, the initial investment may deter some organizations from adopting edge computing.

Integration Complexities with Existing Systems:

Integrating edge computing with existing IT systems and industrial processes can be complex and time-consuming. Many organizations rely on legacy systems that were not designed with edge computing in mind. Retrofitting these systems to support edge computing can involve significant modifications, including software upgrades, hardware replacements, and changes to network infrastructure.

Ensuring seamless communication and interoperability between edge devices, cloud platforms, and existing enterprise systems requires careful planning and coordination. Organizations may need to work with multiple vendors to deploy edge computing solutions that are compatible with their existing infrastructure.

7. FUTURE TRENDS AND THE ROLE OF EDGE COMPUTING IN INDUSTRIAL SYSTEMS

Emerging Technologies: 5G and AI Integration with Edge Computing

The integration of edge computing with emerging technologies like **5G** and **Artificial Intelligence (AI)** is set to drive significant advancements in industrial systems.

- **5G Integration:** The rollout of 5G networks will play a crucial role in enhancing the capabilities of edge computing. With its low latency and high bandwidth, 5G will enable real-time data processing at the edge with even faster speeds. Industries that rely on mission-critical applications, such as autonomous vehicles, industrial robotics, and smart cities, will benefit significantly from the increased data transmission speeds and reduced latency offered by 5G.

For instance, in **autonomous manufacturing environments**, edge computing combined with 5G will facilitate seamless communication between robots, machines, and control systems. Real-time data processing will be more efficient, enabling smarter operations and faster response times, particularly in dynamic and high-speed production lines.

5G-enabled IIoT devices will allow manufacturers to deploy more sensors and connected devices in their operations, capturing an even greater volume of data. This increase in connected devices, combined with edge computing, will lead to better and faster decision-making processes.

- **AI Integration:** The fusion of edge computing with **Artificial Intelligence (AI)** technologies will enable more sophisticated real-time decision-making. AI models, such as machine learning algorithms, can be deployed directly on edge devices to analyze data locally without needing to send it to the cloud for processing. This allows for faster decision-making, enhanced automation, and more intelligent responses to changing conditions in industrial settings.

AI-powered edge computing will enable **predictive analytics** in various industries. For example, in manufacturing, AI algorithms can predict equipment failures by analyzing sensor data in real-

time. In logistics, AI can optimize routing and scheduling for delivery fleets, while in healthcare, AI can assist in real-time monitoring and diagnosis based on patient data from wearables or medical devices.

The combination of **AI with edge computing** reduces dependency on cloud resources, lowers operational costs, and enhances the flexibility of AI models by allowing them to operate independently at the edge.

The Future Potential of Edge Computing in Transforming Industrial Landscapes

Edge computing is expected to play an increasingly critical role in transforming industrial landscapes across several sectors.

- **Manufacturing:** The future of edge computing in manufacturing will involve **intelligent automation** at an unprecedented scale. Edge computing will enable smart factories to not only automate physical tasks but also make real-time decisions based on sensory data. This will result in improved productivity, reduced downtime, and better-quality control. Machine learning algorithms running on edge devices can continuously adapt production processes to optimize efficiency based on real-time data analysis.

Robotic systems integrated with edge computing will become more agile, capable of responding to changes in the production environment without requiring centralized control. This will reduce response times and improve overall manufacturing flexibility.

- **Smart Cities:** Edge computing is expected to be a key enabler of **smart city initiatives**. By processing data at the edge, smart city applications—such as traffic management, energy distribution, waste management, and environmental monitoring—can operate more efficiently. For example, **real-time traffic flow management** powered by edge computing can reduce congestion, optimize traffic light timings, and ensure better resource utilization.

Smart grids using edge computing will be able to manage energy distribution more effectively, integrating renewable energy sources and adjusting in real time to energy consumption patterns. This will improve grid reliability and help cities meet sustainability goals.

- **Healthcare:** The healthcare industry is poised to benefit significantly from the integration of edge computing, particularly with the rise of **remote patient monitoring**. Real-time data analysis of patient vitals and condition, using wearable health devices and smart sensors, will help healthcare providers make better decisions. With edge computing, doctors can receive alerts on critical changes in patient status, allowing for quick interventions and improving patient outcomes.

As healthcare systems increasingly rely on **IoT-based devices** (such as connected medical instruments and personal health devices), edge computing will allow for local data processing, providing faster insights and reducing dependence on centralized servers.

Predictions for Widespread Adoption across Various Industries

The widespread adoption of edge computing is expected to accelerate over the next few years, fueled by technological advancements and the growing demand for real-time decision-making.

- **Industrial Sectors:** Edge computing will become deeply embedded in sectors such as **manufacturing, logistics, agriculture, and energy**, enabling automation, predictive maintenance, and real-time optimization. **Smart factories** and **smart farms** will increasingly rely on edge computing to process vast amounts of data from sensors and connected devices, allowing for more efficient production cycles and precision farming techniques. In energy management, **smart grids** powered by edge computing will lead to more responsive and efficient energy distribution.
- **Consumer and Retail Sectors:** The retail sector will also adopt edge computing to improve customer experiences. **In-store analytics**, real-time inventory tracking, and personalized customer recommendations will be powered by edge devices that process data locally, resulting in better services and faster responses to customer demands.
- **Transportation and Automotive:** The **automotive industry** will continue to embrace edge computing for autonomous vehicle systems, where the need for real-time processing is paramount. Edge computing will enable **vehicle-to-vehicle (V2V)** communication and **vehicle-to-infrastructure (V2I)** systems to operate smoothly, providing enhanced safety features and navigation capabilities.

In **transportation**, edge computing will play a key role in logistics and fleet management, where real-time data analysis can optimize delivery routes, vehicle performance, and supply chain processes.

- **Healthcare:** The healthcare industry is predicted to see rapid growth in edge computing adoption due to the rise of connected health devices, telemedicine, and real-time patient monitoring. Edge computing will enable these systems to analyze and respond to data instantaneously, improving patient care and operational efficiencies.

The future of edge computing in industrial systems is incredibly promising, with its potential to transform industries ranging from manufacturing and logistics to healthcare and smart cities. Emerging technologies such as **5G** and **AI** are expected to enhance the capabilities of edge computing, enabling faster and smarter decision-making processes. As industries continue to recognize the benefits of edge computing, its widespread adoption will drive efficiencies, improve customer experiences, and pave the way for more intelligent, connected ecosystems. With continued advancements in edge technologies, the industrial landscape will undoubtedly become more responsive, agile, and efficient in the coming years.

Graphs and Charts:

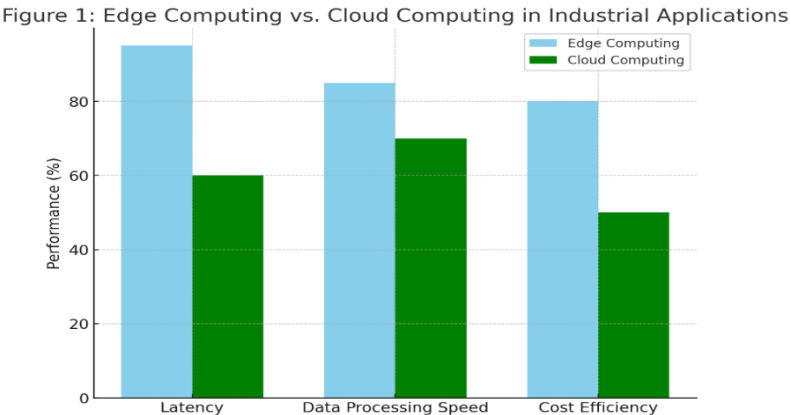


Figure 1: Edge Computing vs. Cloud Computing in Industrial Applications

- A comparison chart highlighting the key differences in latency, data processing speed, and cost efficiency.

Figure 2: Real-Time Decision-Making Workflow with Edge Computing Integration

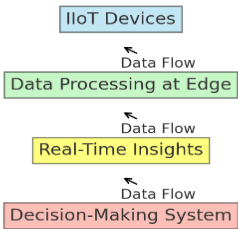


Figure 2: Real-Time Decision-Making Workflow with Edge Computing Integration

- A flowchart illustrating how edge computing processes data in real time from IIoT devices to decision-making systems.

Figure 3: Benefits of Edge Computing in Industrial Environments

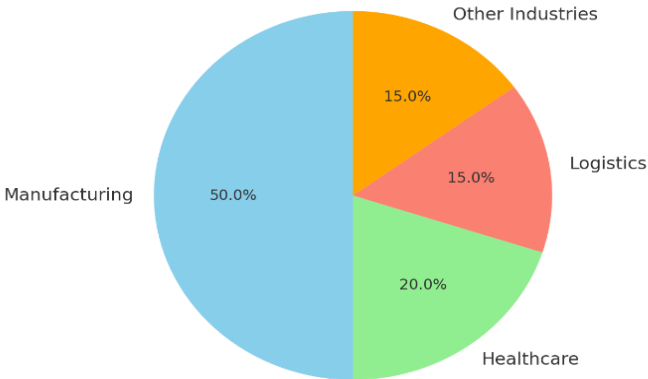


Figure 3: Benefits of Edge Computing in Industrial Environments

- A pie chart showcasing the distribution of benefits across industries, such as manufacturing, healthcare, and logistics.

Figure 4: Market Adoption of Edge Computing in Industrial Applications

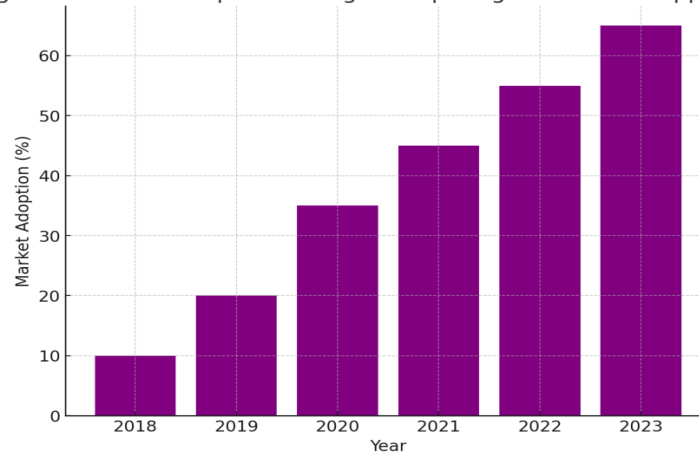


Figure 4: Market Adoption of Edge Computing in Industrial Applications

- A bar chart representing the percentage of industries adopting edge computing over the last five years.

Summary:

Edge computing plays a pivotal role in revolutionizing real-time decision-making in industrial information systems. By moving data processing closer to the data source, it eliminates delays associated with cloud computing and enables immediate responses to changing conditions. Through the integration of edge computing with IIoT devices, industries can optimize operations, improve efficiency, and reduce downtime. The benefits of edge computing are far-reaching, including reduced latency, enhanced operational efficiency, and cost savings. However, challenges such as infrastructure costs, security concerns, and integration with legacy systems remain significant barriers to widespread adoption. The future of edge computing, in conjunction with technologies like 5G and AI, promises further advancements in industrial decision-making systems, offering greater scalability and real-time data processing capabilities.

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