The Role of Internet of Things (IoT) in Real-Time Supply Chain Monitoring

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ABSTRACT

IoT is quickly transforming the supply chain management practice because of increased chances of monitoring and enhancing processes in real-time for IoT. This paper discusses how connected devices and data analytics increase a supply chain's visibility, velocity, and agility. With IoT, the whereabouts of the goods can be tracked at any given time, the state of the environment can also be observed at any given time, and the different stakeholders can communicate at any given time, thus enhancing the decision-making process of the various parties. The technologies that result from IoT can facilitate the supply chain to improve the supply chain velocity by minimizing the lead time and eradicating the human interfaces for inventory and transportation management, thus creating a highly dynamic and effective supply chain ecosystem. The purpose of this paper is as follows: to identify how the application of IoT in the supply chain satisfies and addresses today's challenges, such as demand fluctuations, supply chain disruption, or compliance requirements, and to review trends, challenges, and potentialities of IoT. Finally, the paper proves why IoT is too important for the supply chain's future, as it encounters trends such as increasing globalization, sustainability, and flexibility.

INTRODUCTION

Defining IoT and an Introduction

Internet of Things is the term that describes a world where a colossal number of objects possessing Internet connection capacities can interchange information. These devices include sensors, RFID, cameras, and software that capture, transmit, and process data in real time. IoT uses this interconnection to create a bright space where devices and appliances can manage and operate in the environment by themselves to a certain level of human interaction (Villamil et al., 2020). The Internet of Things is not limited to portable devices such as mobile or home appliances but also industrial and business use such as supply chains.

In the supply chain, IoT is a solution that integrates physically realizable assets, goods, equipment, and transportation means with digital applications for tracking and controlling them. IoT can facilitate the data acquisition for all supply chain processes in real-time decision-making and business process automation (Villamil et al., 2020). The outcome is more effective in managing a supply chain's activities, higher visibility of the position and conditions of goods, and higher flexibility in response to demand or other unexpected changes.

Real-time supply chain monitoring: Importance

It has become necessary to continuously update modern supply chain management to ensure a smooth flow from the supplier to the consumer. It is a worldwide process for the supply chain; in the same way, customers want those things; thus, organizations need to deliver the products on time without any delay, out-of-stock condition, or damaged products (Wang et al., 2020). This can entail the real-time monitoring of goods and services in the supply chain process, enabling the provision of details such as the state of inventories, the condition of transportation facilities, and the delivery time.

Some of the benefits of IoT are realized in real-time. IoTs can feed back information on the status of goods and

equipment in the supply chain. In a real example, it is possible to place some sensors within the shipping container, thus monitoring temperature and humidity to see whether the commodities are in the right condition for stock, especially perishable boasts. Real-time tracking of vehicles is possible with GPS tracking, and this can be useful, especially when it comes to planning the supply chain and in case there are some delays (Wang et al., 2020). This is important in ensuring quality, archives regulatory measures, and customers' satisfaction.

The real-time monitoring capability contributes to supply chain flexibility since firms can modify the SCM activities because of changes in the market or the occurrence of a particular event in a shorter time. However, if, for instance, a storm impacts a shipment, real-time information means can be arranged, making new means of handling, such as rearranging production schedules for the shipment (Outhwaite & Martin-Ortega, 2019). This flexibility ensures that such businesses can continue operating amid disruptive circumstances.

Objectives of the Paper

The primary research question for this paper is to understand the part of IoT for the real-time supply chain and the benefits or challenges it brings to operations, responsiveness, and risk. This paper aims to achieve the following specific objectives: This paper seeks to achieve the following specific objectives:

1. Discuss the fundamental IoT technologies and frameworks required for real-time monitoring in the context of the supply chain.

2. Find out how IoT for real-time monitoring enhances the supply chain process, such as inventory control, transportation, and production planning.

3. Research the best practices of companies applying IoT to improve their supply chain management.

4. Discuss the issues that affect the adoption of IoT in supply chains, the risks of cyber security threats, privacy issues, and the high costs incurred by establishing IoT infrastructure.

5. Evaluate the general trends of how IoT can further enhance more emergent and robust supply chain dynamics.

Theoretical Background

Historical Context of Supply Chain Management

Such changes are marked by the evolution of supply chain management, which is attributable to the increasing demand for effective and efficient SCM. Traditionally, supply chains were basic structures where materials and products moved from the suppliers' side to the manufacturers' side and then to the consumers (Terrada et al., 2022). The increasing globalization, technological development, and supply chain integration have led to the development of complex structures of supply networks with multi-tiers and multi-players from different countries.

SCM in the early part of the twentieth century involved the use of manual systems, which had inadequate capabilities of sharing information and had to rely on telecommunication tools like telephone and fax. For several years, the requirements for better coordination and communication made the firms implement computerized systems in the 1970s and 1980s, like Material Requirements Planning (MRP) systems (Terrada et al., 2022). These systems enabled data collection in various departments and helped provide better inventory control and production options.

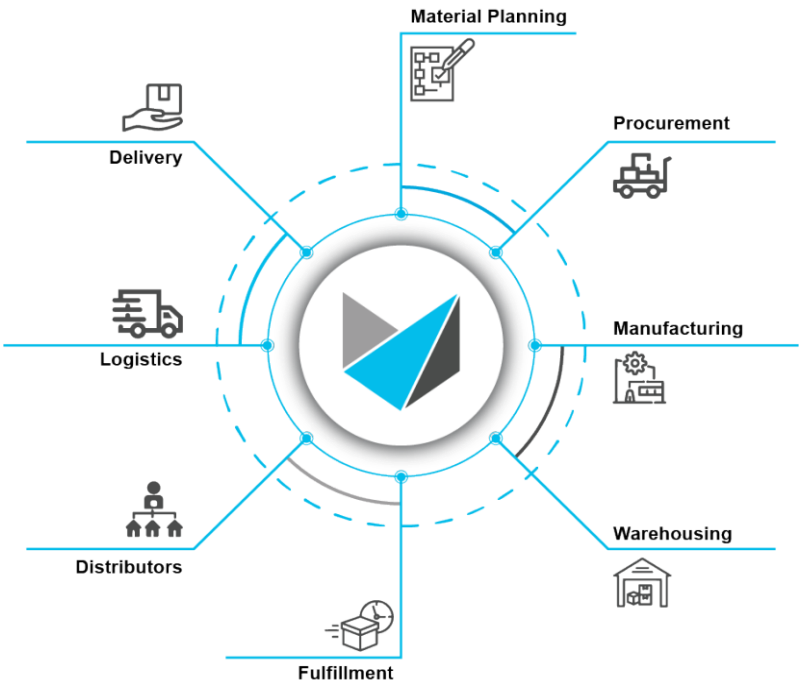
ERP systems launched in the early 1990s also changed the approach to supply chain management because it incorporated all elements of a firm's operations, including purchasing, manufacturing, and distribution. However, even ERP systems supply chain operators were the most limited by their reliance on updates rather than real-time data, and they were not privy to the most up-to-date information regarding the status of the goods and operations.

The Emergence of Real-Time Monitoring in Supply Chain

The requirement for monitoring supply chains in real-time was felt more keenly as supply chains grew in terms of functionality and size. Though good at handling daily operations, the old supply chain systems fail to offer the visibility and flexibility needed in today's ever-evolving market (Outhwaite & Martin-Ortega, 2019). Supply chain operators were mainly using delayed and partially available information sources, which, in turn, caused inefficiencies and delays and definitely – negatively impacted the search for the best opportunities for optimization.

With the IoT technologies in place, there has been a revolution in supply chain management where most processes can be monitored naturally and continuously. This has enabled companies to monitor the movement of goods, environmental conditions, and the occurrence of any problem by embedding IoT devices throughout the supply chain (Taj et al., 2023). Besides enhancing the operational flow, this level of transparency helps in decision-making as one can determine the status of the supply chain at any given time.

While IoT is integrated with other technologies, such as AI and ML, real-time monitoring systems have been enhanced (Taj et al., 2023). The data collected from the IoT devices could be fed to the AI and ML algorithms to search for patterns of interruptions and advise on what to do. For example, by working in a manufacturing line, it is possible to teach the machine learning algorithm to foresee when a particular device will likely break down so that it will be addressed before it develops a major problem.



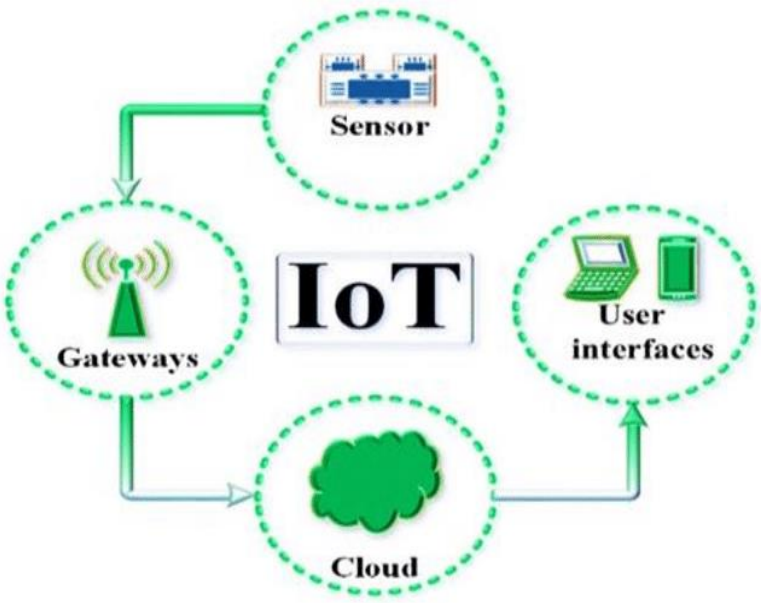
IoT Technologies and Components

Sensors and Actuators

Sensors and actuators are the core of any system and are a component of the IoT setting. While sensors are usually used to record information in the surrounding environment, actuators act according to the data they are assigned to take. In surveillance of the supply chain, sensors are used in shipping containers, vehicles, warehouses, and machinery, among other things, to show the status and position of the goods.

For instance, temperature control is essential for transporting and storing perishable goods in cold chain logistics. The available sensor records the products' temperature and humidity (Taj et al., 2023). These sensors can alarm when a supply chain environment is below or above the set requirements standards so that operations take the supply chain environment; actuators are utilized in controlling devices and equipment using the data from the sensors. In automated warehouses, the actuators control the movements of robotic arms and the conveyor belts through which the goods are transported (Taj et al., 2023). In transportation, actuators can control climate

conditions in refrigerated vehicles to help preserve goods sensitive to extreme temperatures. Sensors and actuators enable many supply chain processes and functions with minimal human intervention, thus enhancing business operations' efficiency.



Message Transfer Patterns (e.g., MQTT, CoAP)

Data exchange between the IoT devices and the central systems depends on reliable communication protocols. MQTT and CoAP are famous examples of communication protocols used in IoT applications.

MQTT: MQTT is a low-fledged protocol primarily established for applications with small bandwidth and low-power devices. It adopts a publish-subscribe broker in which devices place messages within a broker that, in turn, disseminates the messages to interested users (Silva et al., 2021). In this model, it is okay to have many IoT devices, and there will be a free flow of information.

CoAP: Another such protocol is the Constrained Application Protocol or CoAP, which is depicted to work well for low-power devices with restricted capabilities and possibilities. It operates using the UDP, and like HTTP, it uses the request-response model (Silva et al., 2021). CoAP is preferable if one needs fast real-time data transfer in IoT but has no computational means and memory for, for example, HTTP processing.

Due to their network bandwidth and power efficiency, MQTT and CoAP are used in IoT systems (Silva et al., 2021). These protocols enable IoT devices to send data efficiently regardless of context: regions with limited connectivity or mobile devices.

Cloud Computing and Data Analytics

Since IoT deals with immense data derived from things, cloud computing is crucial to IoT frameworks because it provides the needed support to process IoT-generated data (Radhika & Aruna Kumari, 2019). Some current cloud platforms are Microsoft Azure IoT, AWS IoT, and Google Cloud IoT, among others, which offer solutions involving managing IoT devices, collecting data, and storing and analyzing IoT data.

There are numerous advantages to adopting cloud computing, including scalability. The cloud can still increase the storage of the raised volume of IoT data in a supply chain without investing in many on-premises devices (Radhika & Aruna Kumari, 2019). The approach helps businesses build up their IoT skills in implementing and managing IoT environments while not needing to focus on infrastructure boundaries within the traditional IT environment. Besides computing resources and data storage, cloud solutions can provide data analytics tools and IoT data processing to extract valuable information (Radhika & Aruna Kumari, 2019). For instance, using machine learning, forecasting is easier when equipment is most likely to develop a fault, thus calling for early repair. Predictive analytics could also predict the demand and help stocking and scheduling production processes.

Real-time data processing also plays a significant role in cloud-based IoT platforms, where businesses can monitor their supply chains in real-time and then address challenges as they occur (Radhika & Aruna Kumari, 2019). The above capability is handy for industries that handle perishable goods like food products or any goods with a tight delivery time frame, like pharmaceutical products or any manufacturing products that may be sensitive to time.

IoT Platforms and Software

IoT platforms focus on managing devices, gathering data, and analyzing data that can be useful for supply chain improvement (Villamil et al., 2020). These platforms consist of tools for devices and data management, security, and analysis of results, thereby simplifying the IoT deployment and enhancement.

Regarding the platforms applied in supply chains, some of the most suitable IoT Platforms Include Microsoft Azure IoT, AWS IoT, and Google Cloud IoT (Villamil et al., 2020). These applications offer several services that can be availed of based on the business's particular requirements. These include monitoring services, data analysis and reporting services that can be done in real time, predictive analytical services, and alert services.

Some IoT platforms also integrate with other applications in an enterprise, such as ERP and WMS, which provide a broader perspective on the supply chain. This is also good for businesses since it improves operation Performance by collecting data from many sources and ensuring that all aspects of the supply chain are in order.

Apart from enabling accurate real-time monitoring of the devices, IoT platforms have also integrated functionalities to secure the data being transferred or stored on them. One of the significant problems within the Internet of Things is security, including health and finance (Villamil et al., 2020). Encryption, authentication, and access control mechanisms address data interception and modification on IoT platforms.

Real-Time Data Collection and Monitoring

Collecting and monitoring data by IoT in real-time are instrumental for supply chain managers in making proper decisions in supply chain management due to the availability of tools and information. Real-time data results in better auditability and knowledge of processes, which allows restructuring and optimization of the process, cost savings, and customer experience enhancements (Vila et al., 2023). This section will discuss the type of data collected within the supply chains, the methods employed in data collection and integration, the issues of real-time data acquisition, and their solutions, respectively.

Types of Data Collected

In IoT-driven supply chain monitoring, the types of data collected can be broadly categorized into several key areas. In IoT-driven supply chain monitoring, some of the collected data can be grouped into the following categories:

Location Data: GPS technology and RFID sensors help relay the time and position of various assets, vehicles, shipping containers, or individual goods. Such details assist supply chain management in overseeing the movements of consignments and enhancing field routes and time taken (Silva et al., 2021). Another equally important aspect of controlling theft and losses is the geographical position of the items, from their suppliers to the consumers.

Temperature and Humidity: Other critical factors that may apply to perishable products like food, pharmaceutical, and chemical supply chains include Temperature and Humidity. The former parameters are managed in real-time through Internet of Things sensors to ensure that the goods are stored and transported properly (Vila et al., 2023). Deviations from the set thresholds make the equipment and alarms for corrective actions that prevent product spoilage or damage. Specifically, cold chain logistics management relies on temperature as the primary product quality attribute.

Vibration and Shock Data: Products like perishable goods, fodders, or chemicals can have different implications if they are exposed to a high or a low temperature during transportation. In contrast, other fragile products like electronics or delicate machinery may be damaged due to vibration or shock during transportation. These

conditions can be monitored using IoT sensors, and the information they generate will enable supply chain managers to evaluate the probability of damage and develop ways of preventing it (Vila et al., 2023). Such data is beneficial for industries that manufacture products that must be of high quality and reliability.

Inventory Levels: IoT systems allow for real-time inventory monitoring by feeding data from several points of sale, warehouses, and distribution centers (Silva et al., 2021). RFID tags and other smart devices in the supply chain help the manager monitor the stock and the movement of the products within the buildings, and the stock should be adequate to meet customer demand without the need to purchase more.

Operational Performance: IoT devices can also gather information on the productivity of machinery and equipment the moment they are in use (Vila et al., 2023). These include aspects such as the level of usage of the machines, the amount produced, and the frequency of maintenance. This data is useful in industries where equipment may develop faults, disrupting the production process and, thereby, a lot of loss. When assessing operational performance, a business person can predict the need for maintenance and equipment usage.

Methods of Data Collection and Integration in IoT-Enabled Supply Chains

Specifically, regarding IoT in supply chain management, data acquisition and integration are critical in achieving real-time visibility with the right decision. This process involves applying multiple technologies and methods of acquiring, communicating, and processing data in various supply chain locations, as Khan et al. (2022) pointed out. Incorrectly applying these methods may enhance an organization's operating performance and flexibility and gain insightful information about the structure of the supply chains.

Sensor Networks

The application of sensors mainly results in data collection in an IoT-enabled supply chain. IoT devices are sensors capable of monitoring data from their environment at any time (Khan et al., 2022). For instance, temperature sensors are used to monitor the temperature of the transported goods and those stored to ensure that the perishable products are within the proper temperatures. A GPS module tracks the movement of consignment in real time; this makes it possible to see the physical location of goods through the various supply chain networks. Another form of it is the use of RFID tags, which explain the movement of the products through the supply chain steps from the manufacturing companies to the distribution channels or points of sale.

These sensors are generally placed in different areas of the supply chain so that there is adequate coverage for the supply chain (Khan et al., 2022). For example, temperature recording instruments may be installed in reefer trailers and refrigeration storages, whereas RFID is installed on pallets and products. These points are critical for embracing functional specifics concerning the supply chain operations and acquiring opportunities or events to make decisions for regulating and improving the supply chain network operations.

Communication Protocols

Sensors enable data capturing and should be able to send all the data to other central systems for further processing (Taj et al., 2023). To avoid failure, such data must be reported immediately and followed as Related to Specific Communication Protocols. According to IoT, data exchange is done with the help of publish/ subscribe protocols like the MQTT and CoAPs.

MQTT is a messaging protocol employed where resources are scarce, and there is high latency and low bandwidth. It works on the publish-subscribe method, where devices send their data to a broker and receive data from other devices. This makes it suitable for IoT by emphasizing data exchange efficiency. CoAP, in turn, is designed for applications that operate in a constrained network (Silva et al., 2021). Like REST, CoAP also makes effective and sparing use of data regarding its power usage of IoT applications. These communication protocols enable high data transfer rates from the sensors to the central systems and the use of the data in real-time system control.

Cloud-Based Platforms

The cloud is the most popular platform for generating and storing IoT data. Depending on the IoT devices used,

the immense amount of data produced can be handled and stored using the cloud, such as Microsoft Azure for IoT, AWS IoT, and Google IoT. The cloud offers cheaper data storage, which is versatile in storing big data for companies at rather low costs.

Besides storage, Cloud platforms assist in advanced analytics by putting the complete data processing and analytics tools/ services in place. By their very design, such platforms can be utilized to perform numerous business algorithms and data analysis and to come up with the most suitable conclusions (Radhika & Aruna Kumari, 2019). Another advantage is real-time data accessibility and the ability of supply chain managers to monitor the processes, analyze the outcomes, and make needed decisions from any location.

Also, such platforms can pull data from various sources into the cloud in one place. These platforms get information from several IoT devices, enterprises' systems, and even the business's partners; they provide visibility to the entire end-to-end supply chain (Radhika & Aruna Kumari, 2019). This integration is crucial for achieving integrated visibility towards the downstream of the supply chain and optimizing the supply chain's performance.

Data Integration with Enterprise Systems

For IoT data to be optimally used, it has to be connected with the current enterprise systems like the ERP and the WMS (Rehman et al., 2024). Thus, the integration enables the real-time IoT data to be merged with other operational data that helps the business organization to have insights into their supply chain.

For instance, IoT data can be combined with an ERP system to enhance stock management by analyzing the movement of products and existing stock levels. This integration also improves order fulfillment operations since the system can give real-time information concerning shipment status and time of delivery (Rehman et al., 2024). Also, integrating IoT data in WMS systems facilitates production planning since real-time information regarding inventory and equipment is combined with production schedules.

With IoT data integration into enterprise systems, organizations can get a complete view of their supply chain and improve their operations (Rehman et al., 2024). The integration enables organizations to address change proactively, use data to make informed decisions, and have better supply chain performance.

Challenges and Solutions in Real-Time Data Collection

IoT makes real-time supply chain performance possible and presents new issues that organizations must address and enhance. These difficulties are mainly connected to a large amount of data, the data integration problem, comparatively low data transfer rates, and data protection (Vila et al., 2023). Thus, whenever all the mentioned challenges are responded to appropriately, the IoT can optimize the supply chain of any other business.

Data Overload

Another significant problem real-time data faces during collection is the large amounts of data produced by IoT devices. Supply chain processes span several steps and players, providing information from sensors, instruments, and systems. This may become a problem because of the constant flow of data in multiples of terabytes, especially for organizations without the necessary infrastructure to cater to such big data (Horibe & Muraki, 2017). If well managed, there is likely to be success in capturing important information or slowness in response time leading to supply chain inefficiency.

Businesses should employ superior data analysis techniques and artificial intelligence to deal with data overload. These technologies are intended for Big Data processing and analysis. Applying machine learning means that immense amounts of data can be electronically sorted for irrelevance and outliers while analyzing essential data for decision-making. Furthermore, these algorithms can also conduct the analysis automatically and pick out details not usually seen at first glance (Vila et al., 2023). Overloading data is another area where cloud platforms handle the issue. They present versatile holding and processing methods, which can help an organization expand its data to facilitate real-time data processing requirements.

Data Integration

Another issue is data aggregation, where data collected from IoT sensors, ERP systems, and data procured from outside partners must be amalgamated. The information is usually dispersed within one or many systems, so crafting an end-to-end supply chain picture is difficult (Horibe & Muraki, 2017). This fragmentation could slow decision-making and make real-time monitoring nearly impossible.

To address integration problems, IoT platforms have tools that facilitate the integration of information from sources into one system. APIs and middleware alleviate the problem of locked data and the proper flow of information within the supply chain system (Horibe & Muraki, 2017). When an integrated data approach to SC-OM is applied, an organismic view of an organization's activities is also essential to better respond to changes in the supply chain dynamics.

Latency in Data Transmission

Interferences or slowdown in the transfer of data, which is ironically always a problem when applying the real-time method, are also limitations of real-time monitoring. There is an issue that IoT devices can send updated data to central systems with some delay. This can cause problems like spoilage of perishable goods or the inability to detect equipment failure on time. The vital data transfer aims at real-time monitoring so quick intervention and remedial measures can be initiated.

Some protocols can help organizations minimize latency, and CoAP has less latency than others. These protocols enable messaging in networks where bandwidth availability and a low latency rate are widely beneficial for data movement (Silva et al., 2021). Edge computing is the solution where the data are processed locally at the source and not transferred to the cloud. This approach reduces the distances data must go, and decision-making done close to where the data was or is being collected makes IoT systems more responsive.

Security and Privacy Concerns

Confidentiality and security in IoT systems are always vital, especially when addressing information issues. IoT devices 'are vulnerable to such attacks that will compromise the confidentiality, integrity, and availability of data and disrupt the supply chain.' One area of focus that remains a huge challenge is the security of IoT systems, especially in sectors sensitive to data security, such as the health and financial sectors.

The business must observe reasonable security measures to mitigate security and privacy issues. The approach includes data encryption to secure the information in transit and at rest so that the wrong hands do not tamper. Multi-factor authentication is a security measure that ensures that the IoT systems are only accessed after several forms of identification have been entered. Encryption and authentication mechanisms are other essential factors that increase the security level of data transmissions through communication protocols (Aqeel et al., 2022). IoT platforms also have inherent security features such as users' access rights and real-time monitoring of threats to protect the system against cyber threats.

Case Studies of IoT in Supply Chain Monitoring

IoT technology's use in supply chain management has recorded tremendous success across different industries. Looking at the examples from logistics, retail, and manufacturing companies, we can learn about IoT's changes to data acquisition, processing, and business decision-making (Pechlivanis, 2023). These examples show how companies can use IoT to solve complex problems and realize substantial value across their value chains.

Example 1: IoT in Logistics and Transportation

The IoT technology has revolutionized the advertising log, logistics, and transportation industries (Frias et al., 2023). One of the most revolutionary examples is Maersk, the world's largest shipping company that succeeded in adopting IoT to optimize the functioning of its refrigerated containers for perishing cargo.

An example of IoT applied to Maersk involves putting sensors within the company's reefer containers to provide real-time data on temperature and humidity. Such sensors are installed in the containers to consistently gather

information from the surrounding environment (Frias et al., 2023). All the collected data is then relayed to a central cloud-based system that Maersk's supply chain managers can access.

Another great benefit is the possibility of tracking the condition of perishable goods in real time. For instance, if the temperature is too high or lower than the set limit, a notification is issued to the right people. It also helps to provide immediate feedback in case the temperature goes up or down to ensure that the goods are not spoilt and are in a good state when delivered (Frias et al., 2023). Maersk uses real-time data to improve the transportation route, lowering operating expenses and using less fuel.

Example 2: IoT in Inventory Management

Walmart, one of the largest retail chains with countless outlets and distribution centers, is an inspiring example of how IoT can change the approach to the management of stocks (Miao, 2023). Due to this, the company had to look for a way of ensuring that it could monitor the stock status of its extensive supply chain in real-time; the company resolved to use RFID tags.

The company's shops and warehouses use RFID tags, which allow the constant tracking of stocks in real-time. These RFID tags of the IoT type are scanned in all terminal points of the chain and indicate stock availability (Miao, 2023). From here, this data is sent to Walmart's central ERP or Enterprise Resource Planning system, whereby replenishment orders and inventory control are subsequently handled through technology.

Several significant changes can be attributed to Walmart's integration of IoT. More stockouts and more overstocking have improved the availability of products as well as customer satisfaction (Miao, 2023). Visibility in stock position means that the product required at a particular time is available to avoid wastage and increase the company's overall functioning.

The IoT has seen Walmart incorporating self-scan robots that scan the shelves fitted with IoT sensors. These robots continuously monitor shelves to identify gaps that require replenishment and sound an alarm to the staff members (Miao, 2023). Automation improves stock accuracy and decreases the time and energy used to conduct a manual stock count.

Example 3: IoT in Production and Manufacturing

General Electric (GE) from the manufacturing industry is one of the best examples of how IoT has emerged as an influential technology that has revolutionized production lines (Chen, 2017). One of the giant conglomerates in the industrial manufacturing industry worldwide, GE has integrated IoT solutions into its manufacturing plants to improve efficiency and minimize equipment downtime.

GE uses IoT sensors to track details of manufacturing equipment, including utilization, productivity, and required maintenance, among others. This data is then sent to a central hub and run through a suite of machine-learning algorithms (Chen, 2017). The analysis lets GE anticipate equipment failures and schedule maintenance activities in advance.

The change of focus from the reactive to the proactive approach, in the form of predictive maintenance, has proved beneficial for GE. By predicting flaws likely to arise and cause equipment failure, GE can fix them at the right time, reducing the time it takes for equipment to be out of service (Chen, 2017). It also helps to reduce maintenance costs while increasing general production capacity.

Internet of Things technology has helped GE improve its production line by providing data on production rates and productivity. Using such information, GE can change its production timetables, allocate resources more efficiently, and eliminate various slow-moving cycle times (Chen, 2017). The outcome is a lot of integration and optimization in the manufacturing process, which shows how IoT can radically change operations in manufacturing companies.

Lessons Learned and Best Practices

Some IoT technologies in supply chain management have been revolutionary, although the journey is usually

challenging. These include case studies of Maersk, Walmart, and General Electric (GE), which provide valuable information on how companies can succeed in adopting IoT. In this section, the author captures the main findings and recommendations that can help organizations implement IoT to improve supply chain performance.

Start Small and Scale Gradually

One of the most essential things that can be learned from the case studies is that there should be more focus on the pilot projects before going into large-scale IoT implementation. Applying IoT to all means of supply chain can sometimes be a highly complex process and very expensive. Maersk, Walmart, and GE all started by using IoT technologies in specific fields, such as the condition of containers, inventory, or other equipment (Miao, 2023). In this way, they could experiment with the technology and evaluate the effects and possible problems that it may bring when implemented on a larger scale and with less risk.

It is advantageous to begin tiny as the process enables fine-tuning the strategy, determining areas of operations that may require improvement, and confirming that the technology meets the company's requirements. The gradual scaling strategy minimizes risk; it also enables organizations to develop internal exponents and guarantees that an organization is ready for a large-scale implementation (Chen, 2017). After the technology application has been piloted and verified at a trim level, it becomes possible for companies to integrate the IoT in more sophisticated and sensitive areas of their supply chains.

Invest in Data Analytics

Data gathering is one of the critical activities in IoT, but it is not data that creates the value. Appreciating the volume, variety, veracity, and velocity of data produced, businesses must buy into high-quality data analytics tools and technologies to turn collected data into valuable insights (Radhika & Aruna Kumari, 2019). The case studies show that IoT systems management relies heavily on machine learning and predictive analytics to make sense of the data.

For instance, GE applies machine learning algorithms to data from production machines when they require repairs, improving the machinery's performance during idle time (Radhika & Aruna Kumari, 2019). Walmart employs analytics that allows it to monitor inventory in real-time, which significantly helps satisfy customers' demands and reduce instances of stock out.

The main lesson is that data analytics should be regarded as a core element of the IoT business strategy (Radhika & Aruna Kumari, 2019). Hiring the proper tools and building the appropriate culture of data-driven decision-making may help companies fully realize the latent potential of IoT to enhance an organization's operations, predict tendencies, and more.

Focus on Security

Due to the increase of smart devices embedded in IoT systems, security is a significant factor that must be considered. In IoT systems, there is always a risk of cyber threats and attacks, leading to the leakage of important information, supply chain disruption, and large-scale monetary loss (Aqeel et al., 2022). Proper cybersecurity should be fundamental when organizations design and deploy IoT solutions.

The case studies also underscore the need for effective protective control measures, including encryption, multi-factor authentications, and secure communication protocols. For instance, a data breach is counterproductive in the transportation sector, where tracking the flow of goods, such as perishable goods, in real-time is important. These measures are implemented to protect the IoT systems from being accessed by unauthorized individuals and ensure that important data is not leaked. In addition, security measures are incorporated into the IoT platforms, such as threat identification and control of access to the connected gadgets (Aqeel et al., 2022). Companies must implement these security protocols and ensure they are regularly updated to fight these new threats.

Collaborate with Partners

A supply chain is not always a single chain that connects the buyer and the seller; it is a network that includes

several parties, such as suppliers, manufacturers, distributors, and logistics partners (Mofokeng & Chinomona, 2019). Hence, these stakeholders must work closely to ensure that the IoT data is integrated well and that end-to-end visibility is realized within the supply chain.

The most important and evident lesson that can be learned from the case studies is the usefulness of data sharing and cooperation with partners. For instance, Maersk's real-time tracking of refrigerated containers, essential data for decision-making, is always disseminated to stakeholders, such as customers and other shipping companies (Frias et al., 2023). Such an approach allows us to be sure that all participants understand each other and can quickly react to such circumstances as temperature fluctuation or some route changes.

It also applies to the technical working of IoT, where IoT stakeholders work hand in hand with each other. It is necessary to have compatibility between the IoT systems and the platforms used by the partners to ensure that data can be easily exchanged between the systems. When choosing an IoT standard, companies should also focus on open connectivity, which allows data to be shared easily with other systems (Mofokeng & Chinomona, 2019). A company's standard should clearly define how data will be exchanged.

Benefits of IoT in Supply Chain Monitoring

Improved Visibility and Transparency

The foremost advantage of adopting IoT in supply chain visibility is that it reinforces the visibility of the supply chain across the chain. Sensors, RFID, and GPS modules in IoT facilitate tracking goods through the value chain, from sourcing raw materials to the final consignment delivery (Talpur et al., 2023). Such a constant information feed means suppliers or supply chain managers have a live picture of inventory status, transportation networks, and work-in-progress.

Increased transparency also enhances communication between players in the supply chain, such as suppliers, manufacturers, and logistics companies. When data is shared transparently across the network, decision-makers can address disruptions or bottlenecks more effectively. For instance, if a shipment has been affected by traffic or meteorological conditions, IoT data can send early warnings, which managers can use to change the delivery path or production timetable (Talpur et al., 2023). This level of transparency assists businesses in minimizing lead times and eliminating extra costs that emanate from delays to customers, hence improving their satisfaction with the company.

Also, one gains enhanced visibility of other compliance and regulations that could be in the business (Talpur et al., 2023). IoT technology describes the conditions under which stored and transported goods are stored and archived, especially in the food and medication sectors. Temperature, humidity, and handling conditions that are controlled in real-time ensure food safety and conformity to set food safety standards to avoid any sanctions such as fines or adverse product recalls.

Enhanced Decision-Making and Responsiveness

IoT supply chains, therefore, produce large amounts of data that can be used to analyze the performance of the supply chain systems. The data can then be analyzed using sophisticated techniques that enable better business decisions and more adaptability related to market factors (Talpur et al., 2023). For instance, IoT data about the customers' purchasing patterns would assist the supply chain managers in making necessary decisions, such as how to produce more or order more products for the market in case of a surge in demand rates.

Real-time decision-making from data is appropriate in disciplines that constantly experience many changes or when products have more cycles. Concerning demand forecasts about customers, weather, or transport issues, firms can correct supply chain plans instantly (Talpur et al., 2023). This agility also helps companies quickly respond to market trends and eliminate stockouts and overstocking, contributing to organizations' competitive merit.

It also includes another essential element: the so-called predictive maintenance and equipment monitoring, which are valuable. For instance, in the manufacturing industry, IoT sensors can detect the condition and efficiency of

the equipment to notify the operators of the machinery's problematic status. Through IoT, the use of predictive analytics helps businesses to do maintenance before the equipment breaks down, hence cutting expenses on production wastage due to machine breakdowns (Talpur et al., 2023). One of the significant advantages of having accurate data is that, through tool condition monitoring, businesses can be better positioned to know when to repair or replace their equipment, hence cutting down their maintenance expenses.

Increased Efficiency and Cost Savings

Based on the data retrieved, IoT can improve the flow of supplies and significantly reduce costs courtesy of automation. IoT in automation makes some supply chain activities less dependent on the workforce in this field, covering from stock management to order processing. For instance, warehouses, where IoT sensors, robots, and intelligent shelves are integrated, can help store, pick, and package products (Talpur et al., 2023). They can quickly determine the number of stocks, find the location of products, and efficiently use space, shortening the time to process orders and cutting labor costs.

In logistics, using IoT to manage fleets can directly result in the best routes that must be taken based on traffic patterns, the weather, and fuel consumption. Fuel consumption can be managed by reducing the time trucks spend on the road and the time they are left running in one place with no cargo to transport, reducing transportation costs, and developing sustainability (Talpur et al., 2023). The data from IoT can enable logistics managers to monitor the health of the vehicles and fuel consumption, thus ensuring that the cars are running at the optimum level and reducing operational costs.

IoT can also help optimize inventory by reducing required inventories while minimizing stockout chances. IoT systems help supply chain managers automate the reordering of stocks because the IoT systems offer real-time information on stocks available in the market (Talpur et al., 2023). This eliminates excess stocks that may become wastes, particularly perishable products easily affected by deterioration.

Risk Management and Mitigation

It has been realized that IoT implementation for supply chain monitoring can be very advantageous when it comes to risk management and control. Each supply chain organization faces the issue of responding to disruptions ranging from natural disasters, equipment breakdown, and occupational instability (Talpur et al., 2023). The approach increases risk management effectiveness since IoT can detect risks as they occur and take the necessary action.

For instance, IoT sensors can measure such factors as temperature, humidity, or mechanical failure in business premises in real time and, therefore, notify businesses of existing risk factors. In the food industry, the IoT can monitor the condition of perishable goods shipped in a refrigerator through a temperature sensor (Talpur et al., 2023). Where situations reach unacceptance levels, it is possible to set automatic alarms and warnings through sensors, whereby managers in the supply chain can take appropriate action to avoid spoilage.

In addition, the IoT system helps identify equipment failure in advance and eliminate this problem before it evolves into costly downtimes (Ahmad et al., 2023). IoT-aided predictive maintenance lowers the probability of equipment failure and assists firms in avoiding unscheduled and expensive repairs.

Challenges and Limitations

Data Security and Privacy Concerns

This has followed the increase in the use of IoT devices in the supply chain, which has created challenges in data security and privacy. IoT devices produce large volumes of data, some of which are sensitive business data, customer information, and insights (Lee et al., 2022). If this data reaches the wrong hands, any business will likely suffer hefty losses, damage to their reputation, or even legal repercussions.

Another weakness in IoT systems is the large number of devices integrated into the system. Every separate device is another potential access point for cyber threats, meaning protecting the whole network can often be challenging. As shown, IoT devices are prone to cyber threats, which may allow hackers to infiltrate networks, steal information, or even take control of devices (Lee et al., 2022). For instance, an IoT sensor protected by a secure code in a warehouse may open the overall supply chain management system and compromise the business data.

IoT devices are resource-constrained and need more computational capabilities to support security solutions such as encryptions, firewalls, and multi-factor authentications (Lee et al., 2022). The limitation results in increased vulnerability to unauthorized access and data leakage.

IoT security must be prioritized in all businesses to avoid these risks. Measures that include end-to-end encryption, secure communication protocols, and regular updates of IoT software can protect the devices from cyber threats. Enterprises must use multiple layers of protection to secure IoT networks, including firewalls, intrusion detection, and access control (Lee et al., 2022). Minimizing new threats and possible errors also requires constant training of the employees to follow cybersecurity measures.

Integration with Existing Systems

Adapting a traditional system with IoT is one of the main issues facing many organizations today. Supply chains today use archaic systems like ERP and WMS, which are incompatible with IoT systems (Lee et al., 2022). Such approaches lead to data isolation and disparate storage wherein information from IoT devices can be disconnected from other systems in an organization, thus providing a narrow supply chain perspective.

IoT data integration with current systems calls for the enhancement of software and hires and training for the staff. IoT devices must interact with legacy systems, creating unique APIs and middleware (Lee et al., 2022). The approach makes the process slow and expensive, especially for organizations with a large and elaborate supply chain management system.

To overcome these challenges, companies must integrate IoT step by step. It is also essential for organizations to adopt a gradual approach in the implementation of the IoT technology in the supply chain, whereby organizations begin with pilot implementation of IoT technology and implement the technology in specific areas of the supply chain before a general implementation of the technology across the entire supply chain (Lee et al., 2022). Also, IoT platforms should be selected with an inbuilt integration capacity with enterprise systems so that the need for integration with other systems is minimal.

Scalability and Interoperability Issues

As the use of IoT increases, there are difficulties associated with IoT architecture growth and compatibility. Implementing an IoT network throughout a supply chain requires connecting hundreds of thousands of devices in multiple plants, distribution centers, and transportation (Ben-Daya et al., 2022). Sustaining this scale entails well-developed physical structures, dependable communications networks, and effective data processing systems.

Another issue that arises while making IoT systems scalable is the compatibility of all the devices and platforms. IoT devices are usually developed by multiple manufacturers and thus possess varying communication interfaces, data representation models, and protection measures (Ben-Daya et al., 2022). This absence of

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standardization creates compatibility problems, which become a challenge when deploying IoT devices into a single platform.

For instance, a logistics firm can have GPS tracking devices from one supplier, temperature sensors from a second supplier, and RFID tags from a third supplier. If these devices cannot interact with each other or the supply chain central management system, it will be tough to have end-to-end visibility and real-time tracking.

To overcome the problems of scalability and interoperability, businesses should use IoT platforms that conform to open standards and protocols, such as MQTT and CoAP. These protocols have been adopted to enable IoT devices within various manufacturers to be compatible with one another and other systems (Ben-Daya et al., 2022). IoT vendors must coordinate with businesses to guarantee that the present frameworks will suit IoT devices and that these devices may be widened when necessary.

Future Trends and Developments in IoT for Supply Chains

Advances in IoT Technology

One of the most critical developments in IoT technology that will affect the supply chain is embracing 5G networks. 5G presents improved data rates, reduced time for transmission, and high connectivity density, amongst others. Such advancements in connectivity will allow more IoT devices to operate effectively in supply chains and improve data and information flow efficiency (Sallam et al., 2023). Real-time tracking and monitoring will be increasingly effective as businesses learn to respond to disruptions as soon as they happen and use precise coordinates to fine-tune supply chain operations.

The other significant development is edge computing. In conventional IoT systems, the devices transmit data to a central location where the data is processed. Edge computing processes data at the source or on IoT devices (Sallam et al., 2023). This helps minimize latency, which is crucial when it comes to supply chain decisions in real-time, for instance, changing the route that a delivery will take or even anticipating that a piece of equipment will fail. Integrating 5G with edge computing can accelerate the supply chain response time while decreasing bandwidth consumption and improving data security since all information does not have to be relayed to the cloud.

IoT is an emerging innovation supported by blockchain technology meant to improve security and transparency in the supply chain. Utilizing blockchain technology to produce immutable records of the transactions and data collected by IoT devices across the supply chain is possible (Sallam et al., 2023). It is most valuable for those industries where origin, legitimacy, and conformity with the standards are significant, such as the chemical and food industries.

Emerging Applications and Innovations

Several changes are expected to arise from integrating artificial intelligence (AI) with the Internet of Things (IoT) in supply chain management. AI-based IoT systems can take advantage of the vast data from IoT devices and support decision-making processes. For instance, AI can provide real-time demand forecasting from sales and stock data, thus leading to better production and usage of resources (Sallam et al., 2023). In logistics, AI can consider the traffic flow and delivery schedules to ensure a real-time route adjustment to avoid lengthy delays, let alone fuel consumption.

One more promising direction that is being developed nowadays is the use of smart contracts based on IoT and blockchain. Smart contracts are self-executing contracts on the blockchain that trigger the performance of an agreement between supply chain partners based on certain conditions. For example, an IoT sensor can execute the smart contract in releasing payment once the goods arrive at a particular place or once the shipment is confirmed to be in good condition, such as perishable goods' temperature and humidity level (Sallam et al., 2023). This automation decreases the dependence on administrative orders, accelerates the process of transactions, and enhances the confidence between the supply chain members.

The application of digital twins is also gradually emerging in the supply of chains. The digital twin is an imitation

of an object or a procedure in the real world that is enhanced through IoT sensors for gathering actual data. In supply chain management, it is possible to create the supply network's digital twin or its components, such as warehouses and vehicles. These models enable the managers to model different conditions, track the performance, and forecast any possible interference (Sallam et al., 2023). For instance, a particular machinery may develop problems in a production line. The digital twin may be able to predict when the machinery might fail, and the necessary repairs may be carried out before the machinery conks off. This predictive capability can make a massive difference to the operation that can otherwise take an enormous hit in terms of time and money.

Predictions for the Future of IoT in Supply Chains

The future of IoT in supply chains is set to be even more interconnected, autonomous, and intelligent. Full integration of IoT in the supply chain is in the future, whereby every item from the supplier, transportation, and even the receiver will be connected and communicated in real-time (Sallam et al., 2023). Such high levels of integration will allow supply chain management to be done with little to no human interference with IoT, AI, and machine learning, making decisions on their own.

Shortly, there will be more automation of warehouses and distribution centers through intelligent robots, drones, and self-driven vehicles connected through the Internet of Things. Bots of various types, including robots and drones, will continue to perform pick, pack, and delivery functions, while autonomous vehicles, including trucks and ships, will transport the goods (Sallam et al., 2023). These technologies will cut labor expenses, shorten delivery time, and increase efficiency. The firms will completely control their logistics operations and real-time IoT tracking.

Another area in which IoT could be linked to sustainability efforts is also a crucial concern in supply chain management. Governments are passing new legislation to ensure a decrease in CO2 and other greenhouse gas emissions in the atmosphere, and the demand for green products is on the rise, thus putting pressure on firms to adopt sustainable strategies. Using IoT to monitor energy, emissions, and resources will assist the company in tracking its sustainability indicators (Sallam et al., 2023). For instance, IoT devices can help improve how delivery trucks move around to consume less fuel or track energy consumption in factories to avoid extravagance. In the long run, IoT will be an essential tool in making circular supply chains where products are remanufactured, recycled, or remade, thus reducing raw material usage and being environmentally friendly.

The issue of cybersecurity will be on the rise significantly as IoT deepens its tentacles in supply chains. As more devices are connected to the Internet, the probability of being hacked rises (Sallam et al., 2023). Companies will have to spend significantly on protecting IoT systems, using encryption, authentication, and blockchain solutions. More and more governments continue developing data protection regulations; IoT systems must also meet these legal requirements.

Integrated supply chain partners will be established as the IoT systems provide the chance to exchange data. IoT-based open-data platforms will help manufacturers, suppliers, logistics service providers, and retailers collaborate in real-time (Sallam et al., 2023). The approach will enhance demand forecasting, eliminate wastage, and enable organizational flexibility in response to disruption. Someday, we might witness common supply channels where many channel members unite their efforts and investments to obtain size benefits.

CONCLUSION

The IoT will drastically change the supply chain by offering real-time monitoring, automation, and data-driven decision-making tools. Introducing IoT technologies helps to improve control over the supply chain, manage business processes, and promptly address the issues in the supply chain (Villamil et al., 2020). This paper's case and theoretical analysis demonstrate that adopting IoT can increase efficiency and savings and decrease risks in supply chain activities.

The gains derivable from IoT implementation include visibility and decision-making, efficiency, and risk management. Businesses must face a few issues like security, integration, scalability, and the high cost of implementation and maintenance. IoT is not easy to implement; it must be done methodically, emphasizing limited trials, secure implementation, and close working with supply chain partners.

In the future, advanced trends, including the use of 5G, edge computing, AI, and blockchain technologies, will add to the strength of IoT in the supply chain (Sallam et al., 2023). IoT's significance will be more critical as organizations adapt to new technologies and customer expectations. Future supply chains will be more intelligent, independent, and greener, bringing about new forms of efficiency.

For businesses and supply chain professionals, the implications of IoT are clear: it will be essential to invest in IoT technologies now to compete within the global complex and fast-growing market. Businesses can develop more effective and more responsive supply chains that are better prepared for future uncertainties with the help of IoT.

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