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USE OF TECHNOLOGY İN THE SUPPLY CHAİN: AN EXAMİNATİON OF THE EFFECTS OF DİGİTAL TRANSFORMATİON ON EFFİCİENCY, TRACEABİLİTY, TRANSPARENCY AND SUSTAİNABİLİTY

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Abstract

Technology change in supply chain management is listed as an application that supports the organization and scope of the supply chain. This study explores the tools available to meet the needs of modern supply chains, ensuring that technology becomes a crucial component of these components and that they operate more successfully and efficiently. The role of technology in supply chain management helps improve value for money, reduce costs, and improve performance in various areas, from logistics and customer service to warehouse management and supplier collaboration. The key to integrating technology into supply management and logistics application development is the enhanced visibility and transparency that enables real-time tracking of goods and materials. These advanced insights, which allow businesses to make changes to their processes and optimize their operations, will help identify potential bottlenecks and inefficiencies in advance. Supply Chain Management (SCM) focuses on security, confidentiality, traceability, transparency, data accuracy, privacy, efficiency, accountability, and trust, all of which have been significantly enhanced by digital technologies. Increasing globalization and competition have driven companies to embrace digitalization, and IoT, artificial intelligence, blockchain, big data analytics, and robotic systems have enabled supply chains to become more flexible and efficient. The study highlights the benefits that technological transformation can provide through a literature review and case studies. The findings demonstrate that digital technologies have become a strategic imperative for sustainable supply chain management.

The purpose of this article is to define the main digital technologies used in supply chains, discuss the impact of these technologies on operational performance and reveal their relationship with sustainability goals.

Keywords: Supply chain management, digital transformation, sustainability, technology, artificial intelligence, blockchain.

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1. İntroduction

Artificial intelligence (AI) and machine learning (ML) have become effective technologies for expanding supply chain management. The way businesses organize, execute, and structure their supply chain activities has been fundamentally transformed by the sophistication of various technologies. Accurate demand forecasting is one of the most important drivers of AI and ML in supply chain management (Banur et al.).

In an era of rapidly digitizing production and global trade, supply chain management has come to encompass not only the physical flow of goods but also the flow of information and data (Ivanov, 2023). Increasing competition, diversified customer demands, and sustainability pressures are forcing businesses to redesign their processes. In this context, the integration of digital technologies plays a critical role in terms of efficiency, transparency, traceability, and environmental performance (Kache & Seuring, 2017).

This study contributes to the emerging literature on digital transformation in supply chain management by highlighting how advanced technologies—such as artificial intelligence, blockchain, digital twins, and IoT—reshape operational performance and sustainability practices. Unlike earlier frameworks that often treated these technologies in isolation, the findings of this paper illustrate their integrated role in enhancing visibility, reducing inefficiencies, and promoting environmental goals simultaneously.

By bridging theoretical insights with practical observations, the study strengthens the conceptual link between technology adoption and sustainable logistics. It reinforces the view that supply chain sustainability should not only be assessed through carbon metrics or regulatory compliance, but also through the lens of real-time data integration, system responsiveness, and digital resilience.

Furthermore, the analysis suggests that operational excellence and environmental responsibility are not mutually exclusive goals; rather, they are converging outcomes of strategic technological deployment. This adds a new layer to traditional supply chain theories, which often overlooked the synergetic potential of digitization and ecological responsibility.

By examining both findings from academic literature and examples of industry practice, the study aims to provide a framework for future research. The questions addressed include: What are the key applications of digital technologies in supply chain management? How effective are digital technologies in increasing transparency, security, and efficiency in supply chain management? What is the relationship between the application of digital technologies in supply chain management and sustainability?

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2. Literature Review

2.1 Digital Transformation and Industry 4.0

The globalized supply chain has brought with it many challenges that must be overcome. Traceability and reliability are among the most important of these. Industry 4.0 has pioneered digitalization processes in the supply chain and logistics fields. The most important support for ensuring integration in supply chain digitalization comes from information technologies. According to McKinsey & Company, organizations could generate between $1.3 trillion and $2 trillion in annual revenue by integrating artificial intelligence into supply chain management. (www.mckinsey.com). According to estimates by PricewaterhouseCoopers (PwC), artificial intelligence could contribute over $15.7 trillion to the global economy by 2030 (www.pwc.com). Artificial intelligence excels at processing large amounts of data, significantly improving demand forecasting. Technological resources like sensors that provide real-time data are making supply chain management more efficient. These next-generation technologies enable the collection of critical operational data, such as orders, inventory levels, transportation networks, labor utilization, and warehouse activities, and make it accessible to all supply chain stakeholders. This allows companies to monitor their supply chain processes end-to-end, enabling greater agility and accuracy in decision-making. By analyzing data, AI enables more accurate forecasts and informed decisions. Technology increases agility in supply chain management. With better access to information and simulations, managers gain better insights, enabling them to resolve problems or generate new company potential much faster. Using technology in supply chain management gives organizations instant access to sensitive, up-to-date data. This allows managers and decision-makers to make informed decisions based on up-to-date information and identify potential problems early.

2.2. Application Areas in the Supply Chain

The use of technology in supply chain management is rapidly changing. Once limited to paperwork and Excel, the process now utilizes advanced technologies such as the Internet of Things (IoT), artificial intelligence, and cloud computing. To better understand the digital transformation in logistics and supply chains, it's crucial to examine the widespread application of supply chain technologies used by businesses. Today, many businesses are integrating technologies such as real-time data collection, automation, AI-based forecasting systems, IoT (Internet of Things) solutions, and cloud-based integrated platforms into their supply chain processes. These technologies enable core logistics activities such as order tracking, inventory management, supplier performance, transportation route optimization, and workforce planning to be conducted more efficiently, transparently, and agilely. Companies with advanced supply chains, in particular, can use these systems to monitor their entire operations end-to-end, enabling them to detect errors early, improve resource utilization, and increase customer satisfaction. This widespread adoption of digital technologies is reshaping logistics management in line with strategic objectives such as achieving competitive advantage, reducing costs, and reducing carbon footprint. Some of the latest technological developments used in the logistics sector are presented in Figure 1.

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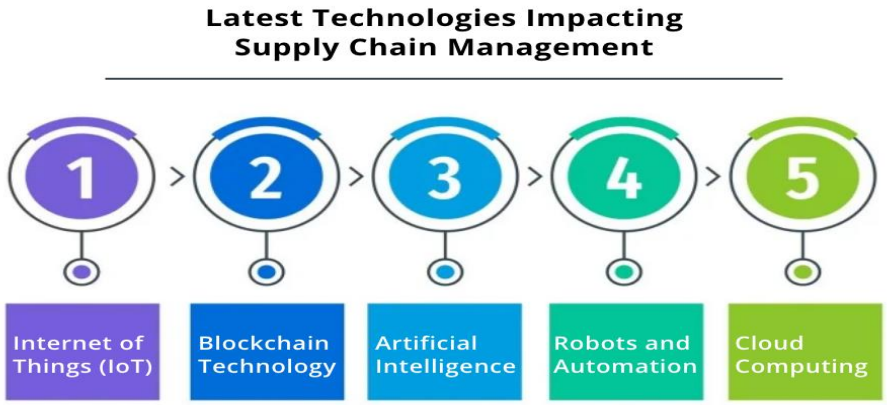

Figure 1. Latest Teknologies İmpacting SCM

2.2.1 Blockchain technology is a decentralized, distributed, immutable ledger technology that stores and records data. It is used in various sectors, including supply chains, smart contracts, property records, healthcare, banking, finance, and more (Kolehmainen et al., 2019). Each block contains specific information, a timestamp, and a link to the previous block, thus forming a chain. Its most significant process contributions are traceability, tracking, and smart contracts. Smart contracts, a key component of the underlying infrastructure of blockchain technology, make it possible to create self-executing agreements with pre-programmed rules and conditions. By automatically matching transactions and processes on the blockchain, smart contracts increase efficiency, speed, and security, respectively. In a trustless and decentralized environment, smart contracts enable parties to execute agreements without the need for intermediaries or a central authority. This allows them to minimize costs and increase transparency (Andrian et al., 2018).

From a traceability perspective, blockchain technology can be used in supply chains to track all steps, from the transformation of a product from its raw material to a product, its delivery to contracted companies for sale, the tracking of the entire warranty period after the product is sold and the recording of any repairs, the entry of the new owner into the system if the product changes hands, and finally, its recycling after it becomes unusable. In this way, blockchain technology provides a reliable and verified logistics system and supply chain information exchange network (Takaoğlu et al, 2019).

This network also allows tracking of all distribution stages of finished products. Walmart has successfully tested blockchain technology twice. Pork produced in China and mangoes grown in Mexico are tracked throughout their journey from producer to end consumer. This tracking capability is crucial in cases of recalls that threaten public health (Sharma & Kumar, 2021).

In the event of a food breach, it will be easy to identify infected product batches. Destroying only the infected items will not be necessary; managing such incidents will prevent the destruction of

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entire stock, thus avoiding significant costs. This is crucial for both protecting public health and limiting potential damage to a company's brand.

All network users can simultaneously view all transactions occurring on the chain. Access to data is public. Storage via distributed ledgers prevents data in the system from being corrupted or altered. Because records cannot be altered and data is verified by multiple nodes, process control increases, which in turn increases trust in the system. Because all historical information can be traced back, this can increase predictive capacity. Because all information in the system is recorded unanimously and in a controlled manner, data accuracy and quality are high. Because the system itself offers a high level of security, the effort to implement measures against cyberattacks within the existing system can be reduced, and the costs of such measures can be reduced. Because transactions and controls are automated, the number of human errors is reduced. Due to the system's operating system, data is stored in multiple locations, and this information can only be changed with the consensus and approval of network participants.

As seen in Figure 2, blockchain applications can be used to monitor the entire supply chain management process simultaneously and transparently at every step, using RFID, barcodes, automatic ID scanners, and other similar methods (Bakan & Şekkeli, 2019). Blockchain technology, which will be integrated into the food supply chain, is a system that can eliminate customer concerns by ensuring consumers consume reliable, transparent, traceable, and high-quality products (Yıldızbaşı & Üstünyer, 2019).

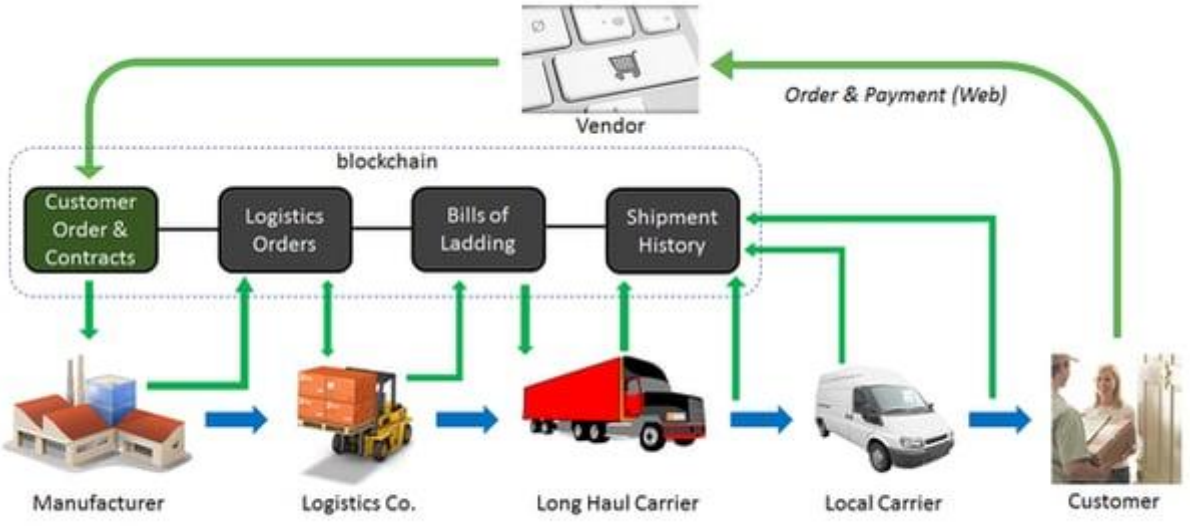

Figure 2. Blockchain Work Flow

2.2.2 Digital twin technology: A digital twin is a virtual simulation that mirrors a real-world supply chain, provides insights into its dynamics, and predicts outcomes. It enables the creation of a virtual copy, or mirror image, of a real-world system, process, or object, offering opportunities

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for innovation, increased efficiency, and decision-making (Menon et al., 2023). Thus, digital twins enable product designs, inventory management, material usage, transportation, and lead times to be easily and accurately adjusted and optimized (Lam et al., 2023). Digital twin applications in operations, logistics, and supply chain management are particularly relevant for operational traceability, transportation maintenance, remote assistance, asset visualization, and design customization. Moshood et al. (2021) stated that supply chain visibility is crucial and that recently developed digital technologies should be utilized to achieve and maintain full visibility across a global supply chain network (Moshood et al., 2021).

Abideen & Mohamad (2021) used the DT approach to examine and analyze various operations within manufacturing and supply chain systems and measure their impact on organizational performance and development. Digital twins increase organizational efficiency by identifying trends and simulating the impact of process changes. For example, digital twin models can predict outcomes, evaluate benefits, and estimate return on investment before implementing changes. A company can use digital twin models to redesign its global operations by simulating various scenarios, such as production levels, inventory management, and product delivery strategies. Digital twins provide a comprehensive, end-to-end view of supply chain processes, making it easier to identify and resolve bottlenecks with minimal human intervention. For example, a digital twin of a shipment uses sensor data to monitor performance and identify issues during shipping and delivery. This data-driven approach enables faster problem resolution and more agile supply chain management. Digital twin technology helps optimize transportation and facilities by analyzing how fluctuations in demand and supply impact physical locations and support systems. Digital twins leverage real-time data to improve transportation planning and resource allocation, improving efficiency.

The exponential growth of the supply chain digital twin market can be attributed to several key factors driving its expansion. First, the increasing integration of advanced technologies such as IoT devices and AI has accelerated the development of advanced digital twin models that improve the accuracy and efficiency of supply chain operations. Second, the growing demand for predictive analytics and real-time data insights has encouraged businesses to adopt digital twins, enabling them to predict market trends, optimize inventory management, and streamline manufacturing processes. Figure 3 shows that the global supply chain digital twin market size is projected to reach approximately US$8.6 billion by 2033, growing at a CAGR of 12.03% from 2024 to 2033 (visionresearchreports.com).

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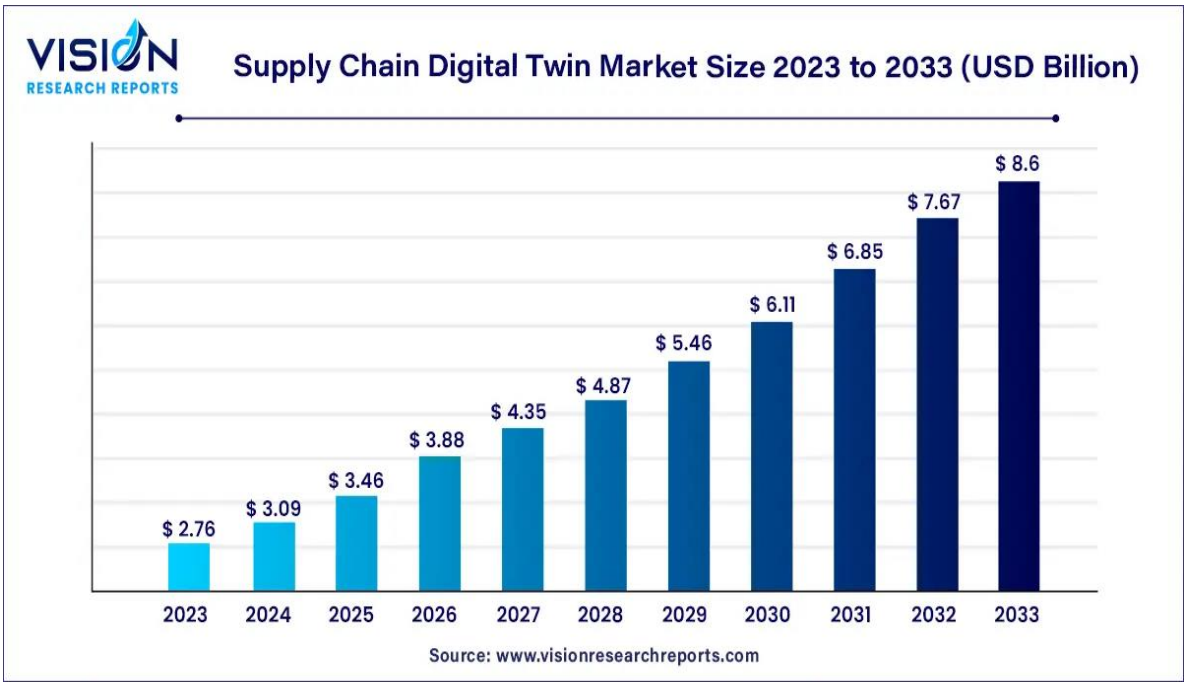

Figure 3. Supply Chain Digital Twin Market Size 2023-2033

The benefits of digital twin (DT)—increased efficiency through reduced traffic congestion, alerts for controlled areas, temperature monitoring, full traffic visibility, and the projection of real-time operational data—have accelerated the digitalization of supply chains and enabled the integration of physical systems and digital networks. IoT (Internet of Things), cyber-physical systems, and AI-powered automation solutions enable real-time management of inventory and production processes (Tjahjono et al., 2017). This transformation allows businesses to develop data-based strategies in their decision-making processes and increase the accuracy of demand forecasts. Despite the potential benefits, there is a lack of awareness among businesses about the capabilities and advantages of Supply Chain Digital Twins. Education about the practical applications and long-term benefits of this technology is vital to overcoming skepticism and encouraging its adoption.

2.2.3 Fully autonomous transport vehicles; Last-mile delivery, a challenge for suppliers and distributors, often creates a bottleneck in the delivery process (zhenhub.com). Even when the product reaches the end consumer, delays are common. Autonomous Vehicles (AVs) are revolutionizing the logistics and transportation management industry by offering improved safety, efficiency, and sustainability. From autonomous trucks and drones to autonomous ships, this technology is transforming the way goods are transported, promising a more efficient and cost-effective future for transportation.. Autonomous vehicles are equipped with advanced technologies like sensors, cameras, radar, and artificial intelligence, allowing them to perceive their surroundings, make real-time decisions, and navigate complex environments with precision. These

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vehicles can optimize their routes, avoid collisions, and operate continuously 24/7, as seen in Figure 4, significantly improving efficiency and reducing costs.

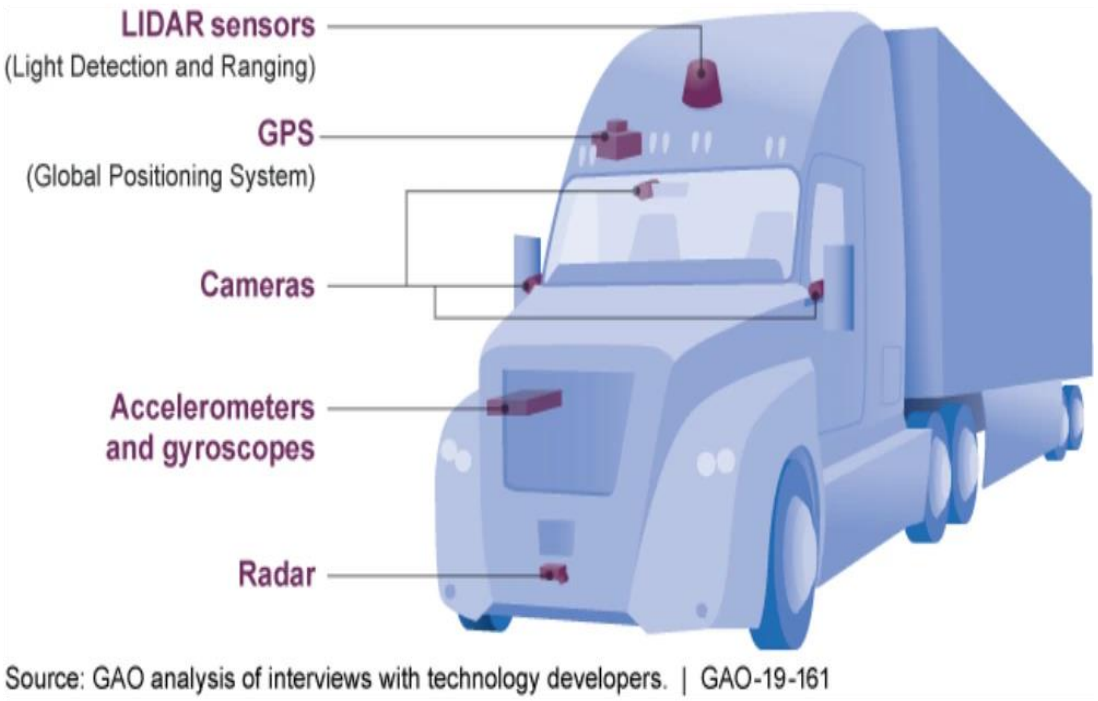

Figure 4. Examples of Automated Vehicle Technologies for Commercial Trucks. United States Government Accountability Office

The benefits of autonomous vehicles include:

1. Increased Safety: Autonomous vehicles can reduce accidents and fatalities on the roads by eliminating human error, which is responsible for a significant portion of traffic accidents.

2. Reduced Costs: Autonomous vehicles can operate continuously 24/7, reducing the need for multiple drivers and increasing efficiency.

3. Improved Efficiency: Autonomous vehicles can optimize routes to avoid traffic congestion and shorten delivery times. For last-mile deliveries, they can reduce the need for trucks to navigate dense urban areas.

4. Improved Sustainability: Autonomous vehicles can optimize routes to reduce fuel consumption and emissions, known as the industry's carbon footprint.

In conclusion, the future of autonomous vehicles in logistics and transportation management is promising, offering significant benefits in terms of safety, efficiency, and sustainability. While there are challenges to overcome, the potential for transformation is very high.

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2.2.4 Robotic, modern warehouses; Automated warehouse vehicles, automated stackers, forklifts, pallet stackers, and small load-handling robots are examples of autonomous vehicles used in warehouses. These vehicles train themselves to follow chosen paths and perform related storage activities using machine learning and deep learning.

Logistics sites and warehouses benefit greatly from autonomous vehicles that simplify safety and mapping challenges. However, because this is precisely the work of forklifts, tow trucks, pickers, and other logistics vehicles, more advanced control capabilities are required for mechanical operations. These autonomous vehicles will need to rely on remote operators to achieve the appropriate level of control. This use case reduces hazards for workers. The added safety also creates unique employment opportunities for people with physical disabilities.

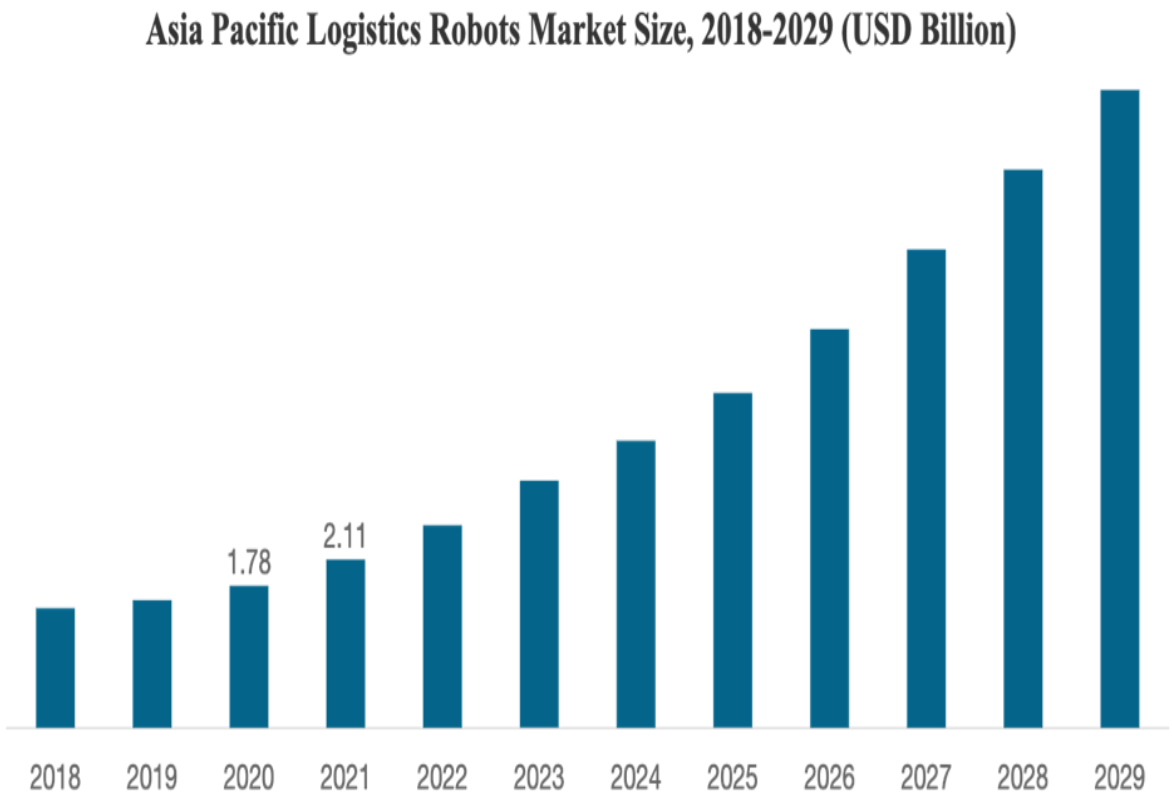

Figure 5. Asia Pacific logistics robots market size.

In Figure 5, The global logistics robots market size was valued at USD 6.17 billion in 2021 and is projected to grow from USD 7.11 billion in 2022 to USD 21.01 billion by 2029, exhibiting a CAGR of 16.7% during the forecast period. Asia Pacific (2020-1.78, 2021-2.11 billion) dominated the logistics robots market with a market share of 34.19% in 2021. The logistics robots market in the U.S. is projected to grow significantly, driven by the growth in the e-commerce industry across U.S. (www.fortunebusinessinsights.com).

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2.2.5 Intelligent load and route planning algorithms; It identifies the most efficient, cost-effective, and safest routes for deliveries. This feature not only speeds up delivery times but also increases the overall efficiency of logistics and supply chain operations. Empty miles refer to the distance trucks travel without carrying a load, which increases operating costs, fuel waste, reduces fleet efficiency, and harms the environment. Reducing empty miles improves resource utilization and makes operations cost-effective. In distribution operations, striking a balance between delivery volumes, fleet size, and operational efficiency is particularly challenging.

The algorithms are perfect for businesses or vehicle owners who want a reliable, mobile-first route planner to optimize delivery logistics and improve customer communication. Figure 6 presents the delivery optimization workflow.

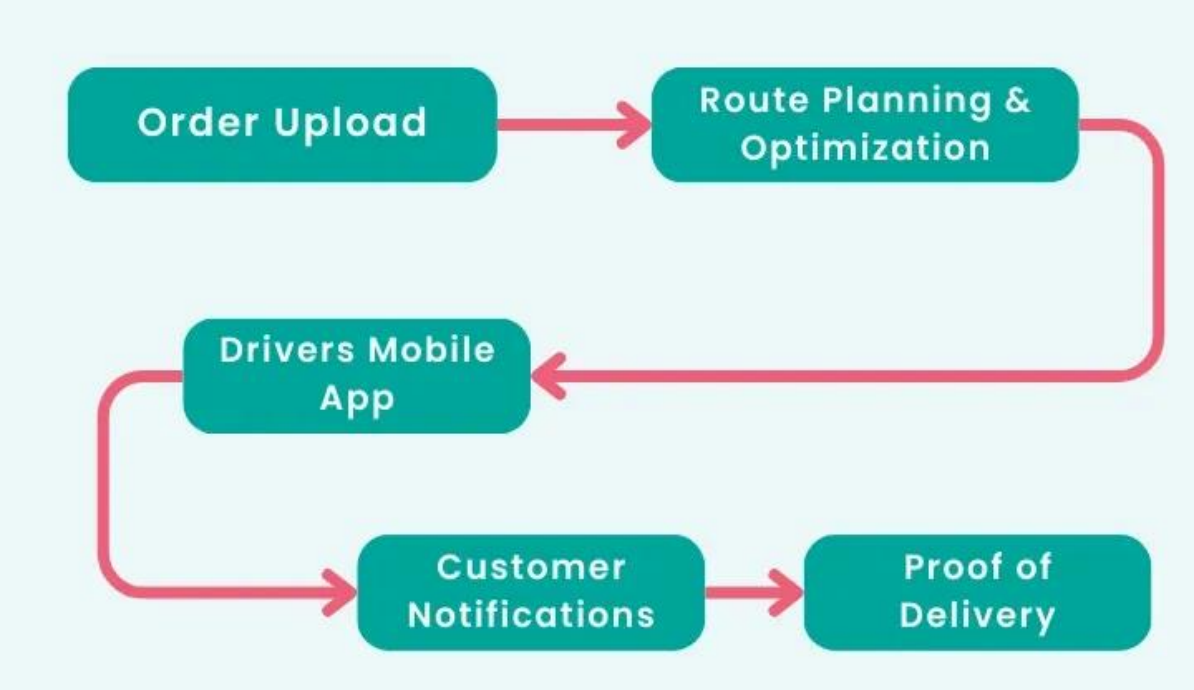

Figure 6. Delivery optimization

Load planning, or optimization, is a multi-step approach that utilizes automation to achieve the following benefits by analyzing vehicle capacity, cargo volume, dimensions, delivery routes, and other factors. Figure 7 presents the benefit processes:

Lower Fuel Costs - Fuel prices are a key cost driver affecting profitability, factoring in factors such as truck maintenance, driver wages, tolls, and truck lifespan. Implementing measures like efficient routing, fuel-efficient driving, and adequate maintenance results in a lower cost per mile and increases the profit margin of each trip**.**

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Fast Delivery- On-time delivery is vital to customer satisfaction and loyalty, especially for time-sensitive shipments. Unplanned delays result in penalties and higher inventory holding costs for the carrier, and can damage the carrier's reputation, negatively impacting overall profitability.

Customer Satisfaction - Delivery timing is the most critical determinant of customer satisfaction. Delivering ordered products completely and within the promised timeframe increases customer confidence. Providing customers with continuous information about the order's release, packaging, shipment, and delivery date increases satisfaction. This creates advantages in terms of customer loyalty and repeat purchases. Integrating the supply chain with CRM directs customer complaints to the appropriate authorities. Last-mile delivery (the process of reaching the customer's door) is the most costly and prone to problems.

To optimize this stage:

• Local warehouses and micro-distribution centers
• Geographic route planning
• Real-time delivery maps should be used.

Administrative Costs - Integrated information systems such as ERP, MRP, WMS, and TMS automate data entry, reporting, order processing, and invoice tracking. This reduces personnel requirements and administrative costs. Coordination among suppliers, production, logistics, and customers can be achieved through a single platform. Real-time dashboards replace legacy methods such as email, phone, and manual forms, reducing time and labor costs.

Figure 7. Intelligent load and route planning algorithms benefit processes

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2.2.6 Wearable Technologies:

The need for accuracy in identifying, processing, and handling packages during product storage and distribution is paramount, and wearable technologies are one solution. By eliminating wasted time, they increase employee productivity, and reduce stress in a fast-paced work environment. Because the computer/wearable device is always on-person, workers can scan barcodes, enter data, search for information, find parts, receive instant alerts, retrieve new information, and work more efficiently by freeing up their hands. Wearable technologies not only minimize human-related errors but also improve quality by detecting product-related errors (Aktaş, 2022).

Smart glasses and smartwatches are two of the most widely used wearable technologies in the enterprise. Other examples of wearable technology include wearable scanners, voice collectors, smart helmets, headbands, smart safety vests, and body cameras.

Businesses have begun using wearable technologies in warehouses to streamline inventory management processes. These devices are hands-free, easily worn on the wrist, hip, or finger, and connect via Bluetooth. They can reliably transmit critical data from up to nine meters away. Wearable scanners not only reduce the cost of ownership but also reduce device downtime.

These lightweight and durable devices allow warehouse workers to use both hands for picking and sorting rather than holding the devices. This helps reduce counting errors, increase efficiency, and reduce labor and equipment costs. These devices also create a safer work experience by alerting workers when postures are unsafe and providing real-time feedback as the user moves. These functions prevent potential injuries before they occur.

As an example of logistics applications, smart glasses, which DHL has launched in the Netherlands, are being used simultaneously by four employees across two shifts. The lenses display information about the item to be picked, its location in the warehouse, and its correct location in the picking basket. Items handled are registered with a ring-shaped scanner, providing hands-free access. Furthermore, other features, such as voice activation and the suggestion of optimal routes within the warehouse, increase operational efficiency, improve picking accuracy, and reduce errors and scanning time (www.dhl.com). Warehouse operators are seeking solutions to increase the efficiency and productivity of their daily warehouse operations, particularly order picking. Many production and logistics systems, including warehouses, still rely on manual labor, and as a result, human availability and productivity have a significant impact on performance and costs. One of the key advantages of voice-guided picking is the reduction in picking errors. Pickers can focus their eyes on the action and their hands are free, increasing efficiency. Pickers can focus on a single item, and terminal usage in freezers is limited. Using voice-guided picking technology offers warehouse operators the advantage of increased pick focus, greater precision, and easier follow-through. Using this technology not only reduces returns but also reduces overall logistics costs.

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Significant benefits such as increased security, increased productivity, and increased employee confidence provided by the application of wearable devices in the logistics sector are helping wearable devices become widespread.

2.3 Technology and Sustainability

Information technologies and digital systems play a direct role in reducing carbon footprints, saving energy and optimizing resource use.

Digital technologies support not only economic performance but also environmental sustainability. Real-time monitoring systems allow us to measure carbon footprints, optimize energy consumption, and reduce waste (Kaya, 2021). Blockchain-based systems strengthen ethical production and green logistics practices by providing transparency across all links in the supply chain (Saberi et al., 2019). The contributions of technological applications to sustainability are presented in Table 1.

Table 1. Technology-Sustainability Relationship

Technology Application	Sustainability Contribution
ERP – MRP systems	Resource efficiency, waste reduction in production planning
IoT & sensor technologies	Energy and resource saving, environmentally friendly operations
Blockchain	Transparent and ethical supply chain
AI & prediction	Demand planning, stock optimization
Advanced logistics software	Carbon emission reduction, less fuel use
Digital traceability solutions	Increasing recycling and reuse rates

Digitalization also facilitates the public transmission of sustainability data obtained throughout the supply chain. By transparently sharing these data in sustainability reports, companies both build investor confidence and strengthen brand reputation. This increases consumer loyalty to the brand and contributes to a stronger position for businesses in global markets. This demonstrates that advanced digital technologies play a catalytic role in green supply chain management (Zaho et al, 2021).

3. Findings and Discussion

Literature and case studies show that digital technologies offer multidimensional benefits in supply chains:

- **Increased Productivity:** A significant reduction in production cycle times has been observed with artificial intelligence-supported planning systems (Taifa & Vhora, 2019).

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- **Cost Reduction:** Thanks to IoT-based monitoring systems, stock surpluses are reduced by an average of 20-30% (Ugbebor et all, 2024**).**
- **Transparency:** Blockchain systems strengthen traceability standards, especially in the food and pharmaceutical sectors (Gerdan et al, 2020)**.**
- **Sustainability:** Digital energy management systems can reduce carbon emissions by 10–25% (Sapci & Considine, 2014).

However, there are also some obstacles to technological transformation. High installation costs, data security concerns, and a lack of skilled labor limit the widespread adoption of digitalization (Shatnavi et al., 2019).

4. Conclusion and Recommendations

This study has explored the transformative potential of digitalization—particularly artificial intelligence (AI) and Internet of Things (IoT) technologies—within supply chain management. The findings reveal that AI-driven tools such as predictive analytics, automated planning systems, and real-time monitoring contribute significantly to reducing production cycle times, minimizing inventory surpluses, and enhancing customer satisfaction. These technologies not only improve operational efficiency but also support broader environmental and social sustainability goals.

Major consulting firms like McKinsey & Company and PricewaterhouseCoopers (PwC) forecast that the integration of AI into business operations can generate trillions of dollars in economic value by 2030. In this regard, the shift towards intelligent, data-driven supply chains is not just a competitive advantage but a strategic imperative.

Recommendations

Strategic Integration of Digital Technologies: Firms should adopt digital transformation not merely as a technological upgrade but as a strategic shift that aligns corporate vision with emerging digital competencies.

AI-Based Decision Support Systems: The adoption of AI in areas such as demand forecasting, inventory optimization, and logistics planning can facilitate faster, more accurate, and cost-effective decisions across the supply chain.

Data Integration and Collaboration Platforms : Seamless integration between stakeholders via cloud-based platforms will increase transparency, speed up decision-making, and improve coordination throughout the supply chain.

Workforce Upskilling and Digital Literacy: The success of digital transformation hinges on people, not just technology. Continuous training in data analytics, digital tools, and software applications is essential for workforce adaptation.

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Sustainability-Oriented Digital Policies: Organizations should align their digital transformation initiatives with sustainability objectives, ensuring that environmental impact, energy efficiency, and waste management are central to technological upgrades.

Support Mechanisms for SMEs: Small and medium-sized enterprises (SMEs), which may lack the resources of larger corporations, should be supported through government incentives, affordable financing, and digital transformation guidance programs.

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