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Optimizing supply chain operations using IoT devices and data analytics for improved efficiency

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Abstract

This paper explores the transformative impact of IoT and data analytics on supply chain operations, emphasizing their role in enhancing efficiency, reducing costs, and improving performance. It addresses key challenges such as lack of real-time visibility, inefficient inventory management, operational delays, and risk management. The integration framework involves data collection, processing, analysis, and decision-making. Emerging technologies like edge computing, blockchain, AI, 5G, and digital twins are highlighted for their potential to further revolutionize supply chains. Strategic recommendations include investing in IoT infrastructure, ensuring data security, fostering skill development, collaborating across stakeholders, and initiating pilot projects. The findings underscore the significance of IoT and data analytics in creating resilient, agile, and sustainable supply chains.

Keywords: IoT; Data analytics; Supply chain optimization; Real-time data; Predictive analytics

1. Introduction

Supply chain operations are the backbone of any industry, ensuring that goods and services are delivered efficiently from producers to consumers. However, modern supply chains face unprecedented challenges due to globalization, increasing customer demands, and the complexity of operations. Traditional supply chain models, which rely heavily on manual processes and fragmented data systems, are often ill-equipped to handle these challenges (Jha, Sharma, Kumar, & Verma, 2022; Shcherbakov & Silkina, 2021). Issues such as lack of real-time visibility, inefficient inventory management, delayed shipments, and high operational costs are common. These problems are exacerbated by the need for agility and responsiveness in a market where customer expectations are continually rising.

The advent of the Internet of Things (IoT) and advanced data analytics offers a promising solution to these challenges. IoT devices, such as sensors and RFID tags, can collect vast amounts of real-time data from various points in the supply chain. This data can be analyzed to gain insights into operations, predict trends, and make informed decisions (Tan & Sidhu, 2022). For example, IoT-enabled tracking systems can monitor the location and condition of goods throughout the supply chain, providing visibility that helps prevent losses and delays. Furthermore, data analytics can process this information to optimize routes, forecast demand accurately, and manage inventories more efficiently.

By integrating IoT and data analytics, supply chains can move from reactive to proactive management. Predictive analytics, powered by machine learning algorithms, can anticipate disruptions and suggest corrective actions before issues escalate. Prescriptive analytics can recommend the best action based on historical and real-time data, enhancing

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decision-making processes. This integration leads to a more resilient, efficient, and agile supply chain, capable of adapting to changes swiftly and maintaining a competitive edge.

This paper delves into the profound impact of IoT devices and data analytics on optimizing supply chain operations, aiming to elucidate their role in enhancing efficiency, cutting costs, and elevating overall performance. Addressing critical challenges in contemporary supply chains, the study explores solutions facilitated by these technologies. Specifically, it examines the transformation of supply chain dynamics through:

- Exploring how IoT enables continuous monitoring and real-time tracking of goods, addressing the persistent lack of real-time visibility in logistics and supply chain management.
- Analyzing how data analytics can revolutionize inventory management practices by optimizing stock levels, minimizing waste, and improving resource allocation. This addresses inefficiencies from inaccurate forecasts and overstocking, optimizing inventory turnover and reducing carrying costs.
- Investigating how the integration of IoT and analytics streamlines operations to mitigate delays and inefficiencies
- Examining the role of predictive analytics in proactive risk management, identifying potential disruptions before they escalate.

2. IoT in Supply Chain Operations

2.1. Overview of IoT

The Internet of Things (IoT) refers to a network of interconnected devices that communicate and exchange data with each other via the internet. These devices, equipped with sensors, software, and other technologies, gather and transmit data in real time. IoT encompasses essential components crucial for its functionality: sensors, connectivity, and data processing (Mouha, 2021). Sensors detect and monitor various environmental factors such as temperature, humidity, and location, playing a pivotal role in supply chain management by providing real-time data on product conditions and movement. These sensors can be strategically deployed on items, pallets, or vehicles, enabling continuous monitoring throughout the supply chain process (da Costa et al., 2022).

Connectivity forms the backbone of IoT systems, facilitating seamless data transmission between devices and centralized systems (Shafique, Khawaja, Sabir, Qazi, & Mustaqim, 2020). Technologies like Wi-Fi, Bluetooth, RFID, cellular networks, and LPWAN ensure reliable communication channels, crucial for transmitting sensor data efficiently across various operational environments. This connectivity infrastructure supports the continuous flow of information necessary for making informed decisions and optimizing supply chain operations (Chaudhari, Zennaro, & Borkar, 2020).

Data processing is integral to transforming raw sensor data into actionable insights that drive operational efficiencies. Once collected, data undergoes processing through advanced techniques such as cloud computing, edge computing, and data analytics platforms (Krishnamurthi, Kumar, Gopinathan, Nayyar, & Qureshi, 2020). These technologies enable the storage, analysis, and interpretation of vast datasets, empowering businesses to derive valuable insights into supply chain performance, customer behavior, and operational trends. By harnessing these capabilities, organizations can make informed decisions, enhance predictive capabilities, and optimize resource allocation across their supply chain networks.

2.2. Applications in Supply Chains

IoT technology plays a crucial role in revolutionizing supply chain operations, offering a diverse range of applications that enhance efficiency and effectiveness across various supply chain stages (Fatorachian & Kazemi, 2021). One key application is in Tracking and Monitoring, where IoT-enabled systems utilize GPS and RFID technologies to provide real-time tracking of goods. This capability ensures end-to-end visibility, allowing companies to monitor shipment locations, track transit conditions, and ensure timely deliveries. IoT sensors, including temperature monitors, enable precise environmental monitoring for perishable goods, ensuring products remain within optimal conditions throughout their journey, thereby minimizing spoilage and financial losses (Tsang, Wu, Lam, Choy, & Ho, 2021).

Another significant application is Predictive Maintenance. IoT devices monitor critical equipment's performance and health, such as trucks, conveyor belts, and refrigeration units. By continuously collecting and analyzing operational data, these devices enable predictive maintenance algorithms to forecast potential equipment failures before they occur. This proactive approach minimizes downtime and extends the lifespan of assets, optimizing operational efficiency and reducing maintenance costs over time (Lee et al., 2020). Furthermore, IoT facilitates Automated Inventory Management

by providing real-time insights into stock levels and inventory statuses. Smart shelves with weight sensors automatically detect inventory fluctuations, triggering replenishment orders when items reach predefined thresholds. This automation ensures that inventory levels are continuously optimized, minimizing the risk of stockouts or excess inventory. Additionally, RFID tags enhance warehouse efficiency by enabling accurate and efficient inventory tracking, reducing manual errors and labor-intensive processes (Sodiya, Umoga, Amoo, & Atadoga, 2024).

2.3. Benefits and Challenges

The integration of IoT in supply chain operations offers numerous benefits. However, it also presents several challenges that need to be addressed. IoT technology offers significant benefits that enhance supply chain operations in various ways. Firstly, it provides Enhanced Visibility by offering real-time insights into the movement and condition of goods throughout the supply chain journey, from production to delivery. This transparency enables companies to pinpoint bottlenecks, optimize transportation routes, and improve operational efficiency by making informed decisions based on accurate data (Shamsuzzoha, Ndzibah, & Kettunen, 2020).

Secondly, IoT contributes to Improved Efficiency by automating critical processes such as inventory management, order fulfilment, and equipment maintenance. This automation reduces reliance on manual labor, minimizes human errors, and accelerates operational workflows. As a result, companies experience faster turnaround times, lower operational costs, and increased productivity across their supply chain operations (Mashayekhy, Babaei, Yuan, & Xue, 2022). Thirdly, IoT facilitates Better Decision-Making by generating and analyzing vast data. Businesses gain actionable insights into supply chain performance metrics by leveraging advanced analytics. These insights empower organizations to optimize resource allocation, enhance demand forecasting accuracy, and swiftly adapt to market fluctuations, improving overall responsiveness and competitiveness (Olawale, Ajayi, Udeh, & Odejide, 2024a).

Moreover, IoT plays a pivotal role in Risk Mitigation by proactively identifying and addressing potential supply chain disruptions. Real-time monitoring of environmental conditions, for instance, ensures the preservation of perishable goods. At the same time, predictive maintenance algorithms prevent equipment failures. This proactive risk management approach ensures operational continuity and minimizes the impact of unforeseen events on supply chain operations (Suresh, Sanders, & Braunscheidel, 2020).

Despite its benefits, adopting IoT in supply chains presents several challenges businesses must navigate. Data Security and Privacy emerge as critical concerns due to the large volume of sensitive data generated by IoT devices. Protecting this data from cyber threats and ensuring compliance with stringent data protection regulations are paramount to maintaining trust and integrity. Integration and Interoperability pose another challenge, as harmonizing IoT devices with existing supply chain systems requires standardized protocols and robust integration strategies. This complexity can be time-consuming and costly, particularly for organizations managing diverse technologies and platforms (Adenekan, Solomon, Simpa, & Obasi, 2024; Duggineni, 2023; Solomon, Simpa, Adenekan, & Obasi, 2024b).

Scalability remains a challenge, especially with the exponential growth in IoT device deployment. Companies need scalable infrastructure and technologies capable of efficiently managing the increasing volume of data and devices to sustain long-term growth and operational efficiency. Furthermore, the initial investment cost in IoT deployment can be prohibitive for small and medium-sized enterprises (SMEs), limiting their ability to adopt these technologies and compete effectively in the market (Mesa, Renda, Gorkin III, Kuys, & Cook, 2022). Overcoming financial barriers through strategic planning and phased implementation is crucial for broader IoT adoption. Lastly, effective Data Management strategies are essential to harnessing the full potential of IoT-generated data. Companies must develop robust data management frameworks to store, process, and analyze data efficiently. This ensures it translates into actionable insights that drive operational improvements and strategic decision-making (Pansara, 2022).

3. Data Analytics in Supply Chain Optimization

3.1. Introduction to Data Analytics

Data analytics involves examining raw data to draw conclusions and make informed decisions. It uses statistical and computational techniques to analyze datasets, identify patterns, and derive actionable insights. In supply chain management, data analytics is pivotal in enhancing efficiency, reducing costs, and improving decision-making processes. By leveraging data analytics, supply chain managers can comprehensively understand their operations, predict future trends, and optimize processes for better performance (Nguyen, Gardner, & Sheridan, 2020; Sarker, 2021).

Data analytics supports decision-making by transforming large volumes of data into meaningful information. This transformation enables companies to identify inefficiencies, forecast demand accurately, manage inventories effectively, and mitigate risks. By integrating data analytics into supply chain operations, organizations can move from reactive to proactive management, allowing them to anticipate and respond to challenges more effectively. This shift not only improves operational efficiency but also enhances the overall agility and resilience of the supply chain (Awan et al., 2021; Rubel, 2021).

3.2. Types of Data Analytics

Data analytics plays a pivotal role in supply chain optimization, encompassing three distinct types: descriptive, predictive, and prescriptive analytics, each offering unique insights essential for strategic decision-making and operational efficiency. Descriptive Analytics analyses historical data to understand past and current performance within supply chains. By employing techniques like data aggregation, data mining, and statistical analysis, descriptive analytics uncovers trends in sales, inventory levels, and transportation metrics. This retrospective analysis enables supply chain managers to identify patterns and anomalies, providing valuable insights that inform future strategies and operational adjustments based on past performance data (Irfan, Sumbal, Khurshid, & Chan, 2022).

Predictive Analytics leverages statistical models and machine learning algorithms to forecast future outcomes based on historical data patterns. In supply chains, predictive analytics is critical in demand forecasting, anticipating equipment failures, and predicting potential disruptions (Aljohani, 2023). For example, by analyzing historical sales data and market trends, predictive models can accurately forecast future demand fluctuations, enabling companies to optimize production schedules, adjust inventory levels, and enhance supply chain resilience proactively (Atitallah, Driss, Boulila, & Ghézala, 2020).

Prescriptive Analytics takes data analysis a step further by predicting future outcomes and recommending specific actions to optimize those outcomes (Lepenioti, Bousdekis, Apostolou, & Mentzas, 2020). Using optimization techniques, simulation models, and advanced algorithms, prescriptive analytics evaluates various scenarios to identify the optimal course of action. In supply chain operations, prescriptive analytics aids in route optimization, inventory replenishment strategies, and capacity planning. For instance, prescriptive models can suggest the most cost-effective transportation routes or optimal inventory levels that balance costs with service levels, enhancing overall supply chain efficiency and customer satisfaction (Poornima & Pushpalatha, 2020).

3.3. Use Cases in Supply Chains

Data analytics enhances various facets of supply chain management, offering valuable insights and optimization opportunities across key operational areas. One of the primary applications is Demand Forecasting, where data analytics leverages historical sales data, market trends, and external factors to predict future demand accurately (Ren, Chan, & Siqin, 2020). Advanced forecasting models consider seasonal variations, market dynamics, and promotional activities. This enables companies to optimize production schedules, manage inventory levels efficiently, and align supply with anticipated demand fluctuations. This capability reduces the likelihood of stockouts and minimizes excess inventory, thereby improving overall supply chain responsiveness and profitability (Kharfan, Chan, & Firdolas Efendigil, 2021).

Route Optimization is another critical use case where data analytics optimizes transportation routes to minimize costs and enhance efficiency. By analyzing factors such as traffic patterns, fuel prices, delivery schedules, and vehicle capacities, optimization algorithms can determine the most efficient routes for logistics operations. This reduces transportation expenses and enhances delivery reliability and customer satisfaction by ensuring timely arrivals and reduced carbon footprints (Ajayi & Udeh, 2024; Tang & Meng, 2021).

Effective Inventory Management is essential for maintaining optimal stock levels while balancing supply and demand dynamics. Data analytics supports inventory optimization by analyzing sales patterns, lead times, and ordering behaviors. Predictive models forecast future demand trends and recommend appropriate inventory levels to prevent stockouts or excess inventory situations. Moreover, prescriptive analytics automates reordering processes, facilitating timely replenishment and efficient inventory turnover, crucial for minimizing carrying costs and maximizing operational efficiency (Kumar, Rajalakshmi, Jain, Nayyar, & Abouhawwash, 2020).

Regarding risk management, data analytics plays a pivotal role in identifying and mitigating supply chain risks. By analyzing data from multiple sources, predictive models can forecast potential disruptions such as supplier failures, demand fluctuations, or geopolitical issues (Araz, Choi, Olson, & Salman, 2020). This foresight enables companies to develop proactive contingency plans, secure alternative suppliers, and maintain continuity in operations despite

unforeseen challenges. Monitoring supplier performance metrics through data analytics further strengthens risk management efforts by identifying reliable partners and addressing performance gaps promptly to uphold service standards and mitigate supply chain vulnerabilities (Kara, Fırat, & Ghadge, 2020). Additionally, data analytics facilitates supplier performance Analysis by evaluating metrics like delivery reliability, product quality, and cost-effectiveness. This analysis identifies top-performing suppliers for strengthening partnerships and negotiating favorable terms. Conversely, it highlights underperforming suppliers, enabling companies to address issues promptly or explore alternative sourcing strategies to ensure consistent supply chain performance and reliability (Adewusi et al., 2024; Negi, 2021; Solomon et al., 2024a).

Moreover, data analytics enhances warehouse optimization by optimizing layout designs, storage configurations, and picking processes. Companies can streamline warehouse operations, reduce labor costs, and improve inventory accuracy by analyzing data on order frequencies, item popularity, and picking times. These efficiencies translate into faster order fulfillment, reduced lead times, and enhanced overall operational productivity, aligning warehouse capabilities with evolving customer expectations and market demands (Kordos, Boryczko, Blachnik, & Golak, 2020). In conclusion, integrating data analytics into supply chain management enables companies to leverage data-driven insights for strategic decision-making, operational optimization, and risk mitigation. By harnessing the power of analytics across these key areas, businesses can achieve greater agility, efficiency, and competitiveness in today's dynamic global marketplace.

4. Integration of IoT and Data Analytics

4.1. Synergy Between IoT and Data Analytics

Integrating Internet of Things (IoT) devices with data analytics creates a powerful synergy that significantly enhances supply chain optimization. IoT devices generate vast amounts of real-time data from various points within the supply chain, such as production lines, warehouses, vehicles, and retail environments. This data includes information about inventory levels, environmental conditions, equipment performance, and product location.

Data analytics, on the other hand, processes and analyzes this data to uncover patterns, generate insights, and support decision-making (Sarker, 2021). When IoT and data analytics are combined, they provide a comprehensive and dynamic view of the supply chain, enabling proactive and predictive management. For instance, real-time data from IoT sensors can be analyzed to predict equipment failures, optimize maintenance schedules, and avoid unplanned downtime. Similarly, data from RFID tags and GPS trackers can be used to monitor the movement of goods, optimize transportation routes, and reduce delivery times (Adama, Popoola, Okeke, & Akinoso, 2024; Solomon, Simpa, Adenekan, & Obasi, 2024a). The integration of IoT and data analytics also facilitates the development of advanced predictive and prescriptive models. These models can anticipate future demand, optimize inventory levels, and recommend actions to mitigate potential disruptions. The continuous feedback loop between IoT data and analytical insights ensures that supply chain operations are constantly refined and improved, enhancing efficiency and responsiveness (Niu, Ying, Yang, Bao, & Sivaparthipan, 2021).

4.2. Framework for Integration

A structured framework is essential to integrate IoT and data analytics into supply chains, encompassing key components of data collection, processing, analysis, decision-making, and continuous improvement. The proposed framework begins with data collection. IoT devices such as sensors, RFID tags, and GPS trackers are strategically deployed throughout the supply chain to gather real-time data. Reliable connectivity through Wi-Fi, cellular networks, and LPWAN ensures secure data transmission across various operational nodes (Chaudhari et al., 2020; Olawale et al., 2024a; Olawale, Ajayi, Udeh, & Odejide, 2024b).

In data processing, collected data undergoes aggregation into a centralized repository using cloud or edge computing platforms. This step ensures that data from diverse IoT sources are consolidated for comprehensive analysis. Data cleaning procedures are followed to preprocess the data, eliminate noise, correct errors, and ensure data consistency and accuracy, which are crucial for reliable insights.

Data analysis within the framework employs various techniques:

- Descriptive analytics summarizes historical and real-time data, offering insights into past and current supply chain performance.

- Predictive analytics utilizes machine learning algorithms to develop models forecasting future trends and events based on historical data patterns.
- Prescriptive analytics recommends optimal actions and strategies for supply chain optimization, enhancing decision-making capabilities.

Real-time monitoring through dashboards and visualization tools enables immediate responses to emerging issues in decision-making. Automated decision systems integrated within the framework execute predefined actions based on analytical insights, such as triggering inventory replenishment or rerouting shipments, to optimize operational efficiency and responsiveness. Feedback and continuous improvement are integral components where ongoing performance monitoring of the integrated IoT and data analytics system identifies areas for enhancement. Iterative refinement of predictive and prescriptive models based on new data and insights ensures continuous improvement in accuracy and effectiveness.

The impact of integrating IoT and data analytics on Supply Chain Efficiency is substantial:

- Reduced lead times are achieved through real-time visibility provided by IoT devices, enabling swift identification and resolution of delays, thereby improving delivery reliability.
- Cost savings are realized through optimized inventory management, reducing carrying costs and minimizing stockouts. Efficient transportation routing and scheduling, guided by data analytics, further reduces fuel consumption, labor costs, and overall transportation expenses.
- Enhanced flexibility enables agile responses to changes in demand, market conditions, and supply chain disruptions. Dynamic decision-making supported by real-time data and analytical insights ensures timely adjustments to optimize operational flexibility.

Improved Risk Management is facilitated by early detection of issues through IoT sensors, allowing proactive measures to mitigate risks and prevent disruptions. Predictive analytics enhances risk assessment capabilities, enabling the development of robust contingency plans for resilient supply chains. Lastly, regarding Sustainability and Environmental Impact, data analytics optimizes resource utilization. It reduces emissions by optimizing energy use, transportation routes, and inventory management practices. This contributes to sustainable supply chain operations, aligning business practices with environmental stewardship goals (Adenekan et al., 2024; Adewusi et al., 2024). In conclusion, integrating IoT and data analytics in supply chains enhances operational efficiency. It improves decision-making, risk management, flexibility, and sustainability, positioning businesses to thrive in a competitive and rapidly evolving global marketplace.

5. Future Directions

5.1. Emerging Trends and Technologies

Several emerging trends and technologies are set to significantly advance the integration of IoT and data analytics within supply chains. Edge computing stands out by decentralizing data processing, bringing it closer to IoT devices. This proximity reduces latency and enables real-time decision-making, which is crucial in environments like autonomous vehicles and predictive maintenance, where immediate responses are critical for operational efficiency and safety.

Blockchain technology offers a decentralized and secure data-sharing approach across supply chain networks. It ensures data integrity and transparency, making it invaluable for tracking products, verifying authenticity, and streamlining stakeholder transactions. By providing a trusted, immutable ledger, blockchain enhances supply chain visibility and efficiency while reducing fraud and errors.

AI and Machine Learning advancements enhance supply chain predictive and prescriptive analytics capabilities. These technologies analyze vast and complex datasets, identify patterns, and optimize operations dynamically. By detecting anomalies in real-time, AI and ML algorithms significantly enhance decision-making accuracy, enabling proactive responses to supply chain challenges and opportunities.

The rollout of 5G connectivity promises to revolutionize IoT integration in supply chains by offering faster, more reliable communication networks. This advancement supports many IoT devices and enables high-volume data transmission in real-time. Enhanced connectivity through 5G facilitates seamless integration of IoT applications across supply chain operations, improving efficiency, responsiveness, and scalability.

Digital twins represent another transformative technology by creating virtual replicas of physical assets, processes, or systems. Companies can simulate and optimize supply chain operations by integrating real-time IoT data with digital twins. This simulation allows for testing various scenarios and predicting outcomes before implementing changes in the physical environment. Digital twins optimize resource utilization, streamline processes, and enhance decision-making by comprehensively understanding how changes will impact the supply chain.

5.2. Strategic Recommendations

Strategic recommendations for companies aiming to integrate IoT and data analytics into their supply chain operations are crucial in ensuring successful implementation and maximizing benefits. First, investing in IoT infrastructure is paramount. This involves prioritizing robust infrastructure that includes sensors, connectivity solutions, and scalable data management platforms. Companies must ensure these investments are future-proof, capable of accommodating technological advancements and evolving business needs.

Data security and privacy are non-negotiable. Implementing stringent cybersecurity measures is essential to safeguard IoT devices and the data they generate from potential threats. Compliance with data protection regulations and industry standards is critical not only for legal reasons but also to maintain trust among stakeholders and mitigate risks associated with data breaches.

Skill development among personnel is equally vital. Equipping employees with proficiency in data analytics, machine learning, and IoT technologies fosters a culture of data-driven decision-making. Continuous learning and upskilling initiatives are necessary to harness these technologies' full potential and adapt to the rapidly evolving landscape of digital supply chains.

Collaboration across stakeholders is key to leveraging the full benefits of IoT and data analytics. Companies can enhance visibility, efficiency, and responsiveness by fostering collaboration and information sharing with supply chain partners. Technologies like blockchain can facilitate secure and transparent data exchange among stakeholders, ensuring integrity and reliability throughout the supply chain network. Strategic alliances with technology providers, academia, and industry peers provide access to innovations and best practices, keeping companies competitive in the dynamic marketplace.

Before full-scale deployment, pilot projects and proof of concepts are recommended. Testing IoT and data analytics solutions in controlled environments allows companies to assess performance metrics, measure return on investment (ROI), and evaluate scalability. Insights from these initiatives enable informed decision-making, minimizing risks associated with large-scale implementations and optimizing resource allocation.

6. Conclusion

In summary, integrating IoT devices and data analytics presents a transformative opportunity for supply chain optimization. Companies can significantly improve efficiency, cost savings, and responsiveness by harnessing real-time data from IoT sensors and applying advanced analytics techniques. The synergy between IoT and data analytics enables proactive management, predictive insights, and informed decision-making across various supply chain functions.

Throughout this paper, we explored the foundational concepts of IoT and data analytics, their applications in supply chain operations, and the strategic implications for businesses. We discussed how IoT enhances visibility, automates processes, and improves resource allocation, while data analytics enables predictive modeling, risk management, and performance optimization.

Emerging technologies such as edge computing, blockchain, AI/ML, 5G, and digital twins promise to further enhance IoT and data analytics capabilities in supply chains. These technologies will enable faster decision-making, greater transparency, and improved operational efficiency. Strategic investments in IoT infrastructure, cybersecurity, talent development, collaborative partnerships, and pilot projects are essential for companies embarking on this journey. These initiatives will pave the way for a more resilient, agile, and competitive supply chain ecosystem.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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