Transforming E-Commerce Logistics: Sustainable Practices through Autonomous Maritime and Last-Mile Transportation Solutions

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Abstract: The logistics landscape in e-commerce is undergoing a profound transformation toward sustainability and autonomy. This paper explores the implementation of autonomous maritime and last-mile transportation solutions to optimize the entire logistics chain from factory to customer. Building on the lessons learned from the maritime industry’s digital transformation, the study identifies key features and proposes a forward-looking autonomous maritime and last-mile transportation system. Emphasizing the role of geospatial technologies, the proposed system employs GIS-based electronic route optimization for efficient goods delivery, integrating onboard and ashore GIS-based sensors for enhanced location precision. A case study was built to analyze the implementation of autonomous means of transport along the route of a product from factory to customer. The integration of autonomous systems shows substantial improvements in logistics performance. Synchronomodal logistics and smart steaming techniques can be utilized to optimize transportation routes, resulting in reduced fuel consumption and emissions. The findings reveal that autonomous maritime and last-mile transport systems can significantly enhance the efficiency, flexibility and sustainability of e-commerce logistics. The study emphasizes the need for advanced technological integration and provides a comprehensive framework for future research and practical applications in the logistics industry.

Keywords: e-commerce logistics; autonomous maritime transportation; GIS-based sensors; artificial intelligence controlled systems; vessel traffic system; last-mile transportation; maritime route optimization; supply chain flexibility; sustainable practices

1. Introduction

In the dynamic landscape of modern logistics and transportation, the integration of autonomous systems across maritime, last-mile, and air sectors stands as a central area of exploration. The increasing demand for speed and reliability, particularly evident during the COVID-19 pandemic [1], has underscored the importance of understanding and enhancing the interactions between key players such as ports, cargo vessels, airports, air cargo carriers, and autonomous last-mile delivery systems. This study aims to provide a comprehensive exploration of these interconnected domains, focusing on their collaborative relationships and transformative potential.

In the ever-evolving landscape of global logistics, maritime transportation stands as the cornerstone, comprising approximately 80% of all merchandise transport volume [2]. This statistic underscores the large role played by maritime systems in facilitating the movement of goods across vast distances. It facilitates the efficient, cost-effective movement of large quantities of goods over long distances, playing a critical role in global supply chains and providing a low-cost alternative to air and ground transportation. Beyond its role
in general trade, maritime transport is essential for the movement of energy resources, food security, and connecting isolated communities [3]. The important role of maritime systems in the world’s economy has fueled extensive scientific and engineering research to improve transportation methods, emphasizing efficiency and security. Against this backdrop, the integration of autonomous technologies in maritime transportation becomes a focal point, warranting a meticulous examination of its implications and transformative potential. The relevance of this study lies in its examination of how these sectors have adapted and collaborated to meet the escalating demands, as well as in providing insights into the transformative potential of autonomous systems in maritime transportation and last-mile delivery.

The current state of research in these areas reveals a great interest in the integration of autonomous technologies. Key publications [4–10] highlight the complexities of the Vessel Traffic System (VTS) of the future (fully autonomous port and traffic management systems, fully autonomous vessels), the challenges of implementing autonomous last-mile delivery systems in urban environments, and the resilience demonstrated by air transportation during global crises. Previous research has asked questions associated with maritime transportation, particularly in achieving full autonomy and addressing safety and regulatory concerns. Similarly, studies on last-mile autonomous delivery systems have explored the intricacies of navigating urban environments, ensuring safety, and adapting to evolving consumer expectations [11,12]. The digitalization of the shipping industry has led the way in unprecedented transformations in the maritime transport and logistics sector. This paper critically reviews the successive information technology (IT)-based generations that have revolutionized the industry, identifying their main features and anticipating future developments. A key emphasis is placed on the role of geospatial technologies in this digital transformation, and the study aims to investigate the impact of digitalization on the shipping industry with a focus on geospatial technologies.

The successive generations of information technology have significantly impacted the maritime transport and logistics industry. This includes computer-based optimization of transport routes, leveraging algorithms to enhance vessel efficiency and reduce fuel consumption [13]. Intelligent sensors and the Internet of Things (IoT) have been proven essential in monitoring various aspects of vessel operations, contributing to improved efficiency and cost reduction [14]. Geospatial technologies, such as GPS and GIS, play a key role in real-time tracking of vessel locations, ensuring better visibility and coordination within the supply chain [15]. Additionally, artificial intelligence algorithms enable intelligent decisions, optimizing vessel routes, predicting maintenance needs, and identifying opportunities for cost savings.

The culmination of these technological advancements leads to the vision of the vessel of the future—an Autonomous Surface Vessel (ASV). ASVs, defined as self-navigating vessels capable of operating without human intervention, represent a focal point of maritime industry research. The Maritime Safety Committee (MSC) defines four degrees of autonomy, ranging from ships with automated processes to fully autonomous ships capable of making decisions independently [16]. The literature on autonomous vessels presents various prototypes with varying degrees of autonomy, showcasing a progression from less autonomous to fully autonomous designs [4,6,10,13,17].

The aim of this study is to provide a forward-looking perspective on the future of e-commerce logistics. By envisioning an interconnected and autonomous transportation system, the research anticipates a transformative shift in how goods are transported and delivered. This anticipatory exploration embraces the complexities and challenges associated with the journey from automation to autonomy, aiming to contribute insights that resonate across disciplines.

The remainder of this paper is organized as follows:

- **Section 2:** E-commerce Logistics and Sustainability—This section discusses the importance of sustainability in e-commerce logistics, focusing on green delivery options, eco-friendly packaging, and energy-efficient warehousing solutions.
• Section 3: Autonomous Maritime Transportation—This section explores the integration of AI and advanced sensors in maritime shipping, highlighting their impact on route efficiency and operational effectiveness.

• Section 4: Last-Mile Transportation Solutions—The focus here is on the deployment of autonomous vehicles and drones for last-mile delivery, emphasizing their role in reducing emissions and optimizing delivery routes.

• Section 5: Integration and Interoperability—Here, we discuss the integration of various autonomous systems and their interoperability within the logistics network, emphasizing the importance of seamless communication between different systems.

• Section 6: Case Study: The Integration of Autonomous Systems in e-Commerce Logistics—A detailed case study is presented to analyze the implementation of autonomous transport solutions from factory to customer.

• Section 7: Challenges and Future Outlook—This section addresses the challenges faced in the deployment of autonomous logistics systems and provides insights into future developments and potential solutions.

• Section 8: Conclusion—The paper concludes with a summary of the key findings, implications for future research, and recommendations for practitioners.

2. E-Commerce Logistics and Sustainability

The sustainability of e-commerce logistics is becoming increasingly vital in a world where environmental concerns are paramount. This segment of the industry is facing a growing demand from consumers for green delivery options [18,19]. Sustainable practices in e-commerce logistics not only involve reducing carbon emissions and promoting eco-friendly packaging but also optimizing supply chains for greater energy efficiency [1]. Embracing green logistics can significantly lessen the environmental impact of online retail, which can have a significant impact given the rapid expansion of e-commerce.

This necessitates a shift toward more sustainable transportation methods, eco-friendly packaging materials, and energy-efficient warehousing solutions. Moreover, there’s an emerging trend toward integrating sustainability metrics into logistics strategies, ensuring that e-commerce companies contribute positively to environmental stewardship while meeting their consumers’ expectations for responsible delivery options.

For the transportation of goods, we can identify three segments: preparation for the transport, long-distance transport and last-mile transport, as depicted in Figure 1. The preparation phase in e-commerce logistics focuses on efficiency and sustainability. This involves selecting environmentally friendly packaging materials and optimizing package sizes to reduce waste and transportation space. Advanced software is used for inventory management and order processing, ensuring that goods are prepared accurately and swiftly for dispatch.

![Figure 1](image.png)

Figure 1. Transportation process of goods, divided into segments.

Long-distance transport in e-commerce logistics has seen a shift toward sustainable practices [20]. Companies are increasingly utilizing fuel-efficient vehicles and optimizing shipping routes to reduce emissions [5,21]. The integration of AI and geospatial technology in maritime and air freight enhances route planning and cargo tracking, contributing to the reduction in the carbon footprint associated with long-haul transportation of goods.

In last-mile delivery, e-commerce companies are adopting eco-friendly transportation methods, such as electric vehicles and bicycles, to minimize environmental impact [22,23]. Technology plays a key role, with route optimization algorithms and delivery scheduling...
software ensuring efficient and timely deliveries. The focus is on reducing emissions while meeting the growing consumer demand for quick and reliable delivery services.

The following sections will explore transformative technologies in e-commerce logistics. The section on autonomous maritime transport investigates the integration of AI and advanced sensors in shipping, focusing on how they enhance route efficiency and operational effectiveness for long-haul transportation. The “Last-Mile Transport” section focuses on the deployment of autonomous vehicles and drones, revolutionizing the delivery process by reducing emissions, optimizing routes, and meeting the rising demand for swift and eco-friendly delivery services in urban areas.

3. Autonomous Maritime Transportation

This section explores how autonomous traffic management systems be implemented near ports, emphasizing the role of the Ashore Operations Center (AOC). The AOC is a pivotal innovation for managing vessel routes near shorelines. Its role is to provide advanced planning of routes and ensure their safe implementation through either direct control or validation of routes proposed by Autonomous Surface Vessels (ASVs). This concept is particularly envisioned for large ports where traffic density is high, and the coordination of diverse vessel types (autonomous and manned) is essential. The implementation of networked AOCs allows for efficient sector-based management and seamless hand-over–take-over of vessels as they traverse different port sectors. Figure 2 depicts the components of a vessel traffic system and the data links between the components (one channel for raw data from sensors and one channel for processed data, instructions, commands and feedback).

![Figure 2](image_url)

The sensor systems onboard vessels and those controlled by the AOC are central to the success of autonomous maritime operations. Onboard sensors are categorized into mandatory (permanent) sensors like GNSS, and task-specific sensors used for precise tasks such as docking. These sensors, including advanced technologies like Sonar, IR, LiDAR, and GNSS, play a critical role in providing accurate data about the vessel’s surroundings, used for collision avoidance and efficient navigation.

The sensors in a vessel traffic system can be divided into two main categories [24]: onboard sensors managed by the ship and ashore sensors controlled by the AOC. Onboard sensors are divided into two categories: essential sensors, like GPS, for fundamental operations, and specialized sensors for specific tasks such as docking. These sensors must be reliable, energy-efficient, and cost-effective, encompassing technologies like GNSS, AIS, Sonar, EO, IR, SAR and LiDAR. These sensors are critical for creating a comprehensive environmental overview to avoid collisions. Task-specific sensors, focusing on precision and...
timeliness, aid in detecting and navigating around nearby objects, especially in congested areas. The critical requirements for the sensors, particularly for the bow sensors must ensure an appropriate range to effectively detect both above-water and submerged obstacles (see Figure 3). Key considerations include the sensor’s range, depth detection, azimuth angle, and elevation capabilities. These parameters are vital for providing sufficient reaction time, allowing the vessel’s AI system to analyze and react to potential hazards. This ensures safe navigation by preemptively identifying and responding to various obstacles, both seen and unseen, in the vessel’s path.

![Figure 3. Vessel traffic system bow sensor coverage requirements.](image)

Ashore sensors, particularly those employing Synthetic Aperture Radar (SAR) technology, complement this system by offering high-resolution imaging capabilities irrespective of visibility conditions. Such a comprehensive network of sensors, spanning land, sea, air, and space, ensures redundancy and the accuracy required for efficient AOC operations. Ashore sensors play a vital role in ensuring high-resolution imaging and accuracy, needed for the AOC’s oversight responsibilities.

The proposed architecture of Artificial Intelligence (AI) neural networks for maritime logistics is based on a “many to many” recurrent neural network model. This model integrates various elements like ship AI (handling navigation and sensor control) and the AOC AI (responsible for traffic management and generating a common operational picture). The network’s design emphasizes feedback loops between all neurons, enhancing the system’s ability to make real-time decisions based on sensor inputs. The use of Field-Programmable Gate Array (FPGA) boards is preferred, in the view of the authors, for their robustness and low latency, crucial for processing time-sensitive signals from various sensors. The architecture also allows the integration of CPU or GPU hardware solutions, adapting to different operational needs. Figure 4 illustrates the designed recurrent neural network architecture for implementation in the system. This network is conceptualized as a complex interconnected system, essentially a network of networks, each serving specific functions within the broader system architecture. AOC’s architecture should be open, in a federated configuration, allowing approaching ASVs to connect to the federal network.

Future operational scenarios in maritime logistics are to be considered, starting from the current state, and working toward a fully automated traffic system. This spectrum of automation presents unique challenges and opportunities for the industry. The need for early adoption of interoperability standards is highlighted to ensure seamless integration across different levels of automation. The gradual transition toward the future states, reveals the importance of standardization to facilitate smooth interactions between automated and traditional systems in maritime logistics.
The recurrent neural network (RNN) architecture employed in this study for processing sensor data on autonomous ships includes two hidden layers. This design choice is motivated by several key benefits like Increased Model Capacity (the inclusion of two hidden layers enhances the network’s ability to learn and represent complex patterns in the sensor data), Improved Feature Extraction (the first hidden layer is responsible for extracting primary features from the raw data, while the second hidden layer further processes these features, combining and refining them into more abstract representations), Enhanced Non-Linearity (each hidden layer introduces non-linear transformations through activation functions, enabling the network to model intricate non-linear relationships within the data) and Efficient Processing (while deeper networks can offer more capacity, they also increase computational demands and pose challenges such as vanishing gradients; two hidden layers provide a balance, offering sufficient complexity to model the data effectively while maintaining computational efficiency, which is desired for real-time processing on autonomous ships).

The authors consider that the architecture proposed in this study best employs the Rectified Linear Unit (ReLU) activation function for the hidden layers. This choice is motivated by several key benefits that align with the requirements of real-time sensor data processing on autonomous ships such as computational efficiency, improved learning dynamics and sparsity.

The process from sensor data to motion control commands involves several steps. In Figure 5, a flowchart diagram illustrates this process, followed by an explanation of the process in each layer of the proposed RNN. In the first step, data are gathered from various onboard sensors and from AOC. In the next step, the collected data are normalized to ensure consistency and any missing or incomplete data are handled to maintain data integrity. All the data are fed into the input layer.

The primary features are extracted from the raw sensor data using the following equation:

\[ h_t^{(1)} = ReLU(W_{hx}^{(1)} \times x_t + W_{hh}^{(1)} \times h_{t-1}^{(1)} + b_h^{(1)}) \]  \hspace{1cm} (1)

and it further processes these features into more abstract representations using the equation:

\[ h_t^{(2)} = ReLU(W_{hx}^{(2)} \times h_t^{(1)} + W_{hh}^{(2)} \times h_{t-1}^{(2)} + b_h^{(2)}) \]  \hspace{1cm} (2)

Situation analysis is performed by the analysis of the processed features to detect obstacles and assess environmental conditions. This step ensures that the ASV is aware of its
surroundings and can identify potential hazards. The next step implies route optimization based on the situation analysis. The necessary adjustments are made to the ASV’s speed and direction to ensure safe and efficient navigation. The COLREG rules are applied to ensure compliance with international maritime navigation regulations. After the decision is made, the specific control commands for the ASV’s motion control systems are generated using the output layer equation:

\[ y_t = W_{yh} \times h_t^{(2)} + b_y \]  

These commands will include adjustments to the propulsion system and steering mechanisms.

In these equations:
- \( W_{hh} \) and \( W_{hx} \) are weight matrices for the recurrent and input connections, respectively.
- \( W_{yh} \) is the weight matrix for the output layer.
- \( b_h \) and \( b_y \) are bias vectors for the hidden state and output layer, respectively.
- ReLU (Rectified Linear Unit) is the activation function applied element-wise.

**Figure 5.** The flowchart diagram illustrating the calculation algorithm, and the process in each layer of the proposed RNN.

In the authors’ view, the Adam (Adaptive Moment Estimation) optimization algorithm is the most suitable for optimizing the recurrent neural network used for the vessel’s autonomous system, because it is well-suited for training deep learning models and is particularly effective for handling the complexities of recurrent neural networks. The learning rate controls how much to change the model in response to the estimated error each time the model weights are updated. For this RNN, the learning rate is set to \( \alpha = 0.001 \). The exponential decay rates for the moment estimates are set to \( \beta_1 = 0.9 \) and \( \beta_2 = 0.999 \). A small constant \( \epsilon = 10^{-8} \) is used to prevent any division by zero during the updates.

The training process terminates when the following criteria are met:
- Maximum epochs: the training runs for a maximum of 100 epochs.
- Convergence threshold: training stops if the change in loss between consecutive epochs is less than 0.001.

The transition from automation to autonomy is a key aspect of technological evolution in the maritime industry. Automation has been instrumental in minimizing human intervention, enhancing efficiency, and reducing errors across various sectors. With the advent of AI, AR, VR, and robotics, the capabilities of automated systems have significantly expanded, yet human oversight remains necessary. However, autonomy represents a more advanced stage where systems are self-sufficient, capable of learning and adapting without human input.

Industry 4.0 marks a new era, building on the previous industrial revolutions. It integrates modern technologies like AI, Big Data, and IoT, fundamentally altering industrial operations. Autonomous robots, a pillar of Industry 4.0, exemplify this shift by performing
complex tasks, interacting with other systems and humans, and continuously learning, thereby streamlining production further [25].

Currently, autonomous systems are prevalent in various sectors, including self-driving cars, UAVs, and AMRs in supply chains [26]. These systems, although in different stages of maturity, highlight the potential for complete autonomy in the near future.

The progression from automation to autonomy offers numerous benefits, such as safer and more efficient operations, lower carbon footprints, and optimized supply chains. While full autonomy remains an aspirational goal, existing semi-autonomous systems are evolving, indicating the direction of future industrial applications. The challenges and barriers to achieving complete autonomy are substantial, yet with rapid technological advancements, the realization of fully autonomous systems is on the horizon.

Building upon the advancements in autonomous technologies, our proposed model for maritime logistics integrates the principles of autonomy into the maritime transport sector. This model centers around the AOC which manages near-shore vessel routes, either by planning and sending routes to ASVs or by receiving and adjusting them to ensure safe navigation. This system is particularly effective in large ports where traffic is managed sector-wise, ensuring smooth transitions between sectors for both autonomous and manned vessels.

The integration of advanced sensor technologies is determined in this model. Onboard sensors like GPS, Sonar, EO, IR, and LiDAR provide essential environmental data, while ashore sensors employ Synthetic Aperture Radar (SAR) technology for high-resolution imaging in various visibility conditions.

The heart of this model is a “many to many” recurrent neural network architecture [27]. This network integrates elements like ship AI for navigation and movement control, and AOC AI for traffic management, providing powerful computation and minimal latency, essential for handling time-sensitive signals from multiple sensors. The proposed architecture can be structured as a federated network, comprised of interconnected yet autonomous sub-networks, able to collaborate to achieve common objectives, where different neural network components work together while maintaining a degree of individual operation (see Figure 6). This architecture could effectively operate as a federated network, benefiting from its inherent traits of scalability, resilience, and decentralized control, which are essential for complex, composite systems like those in maritime logistics.

Figure 6. The proposed architecture for the federated network.
4. Last-Mile Transportation Solutions

Last-mile transportation is a critical component of e-commerce logistics, representing the final step in delivering goods to customers. This segment, often the most complex and costly part of the supply chain, directly impacts customer satisfaction and environmental sustainability. Efficient last-mile delivery solutions are essential for reducing transit times, minimizing carbon emissions, and enhancing the overall customer experience. Innovations in this area are necessary for e-commerce businesses to stay competitive and meet the evolving expectations of modern consumers [28].

The integration of autonomous delivery robots in last-mile logistics represents a significant step toward more efficient and environmentally friendly e-commerce operations, according to one study [23]. These robots are designed to navigate public spaces, interacting safely and effectively with the traffic environment, including cars and pedestrians. Their use addresses the increasing demand for quicker and more sustainable delivery options, particularly in urban areas. The success of these robots relies on their ability to seamlessly integrate into the existing infrastructure and coexist with traditional transportation methods.

Drones have emerged as a powerful tool for enhancing last-mile delivery. They offer a swift and cost-effective solution to traditional delivery challenges. To extend their operational capabilities, a novel approach involves pairing drones with delivery trucks, as proposed by Bi et al. [12]. Trucks act as mobile launch and recovery platforms, expanding the drones’ range and payload capacity. This hybrid system enables drones to cover longer distances and carry heavier packages, making them more suitable for a diverse range of delivery tasks. The combination of trucks and drones illustrates the innovative strategies being developed to optimize last-mile logistics.

These technologies are not standalone solutions but are integrated into the broader e-commerce logistics network. The synergy between autonomous delivery robots, drone systems, and traditional delivery methods creates a multi-layered and highly efficient last-mile delivery network. This integration is supported by sophisticated algorithms and AI systems that manage logistics operations, ensuring timely and reliable delivery to the end consumer.

One way to improve last-mile transportation is the development of multi-modal delivery networks, which combine various transportation methods, like bikes, drones, and electric vehicles, depending on the urban landscape and delivery requirements. This approach can optimize efficiency and adaptability. Multi-modal delivery networks represent a revolutionary approach in last-mile logistics. This system integrates various transportation methods—such as bicycles, electric vehicles, and drones—into a cohesive network, as is presented in Figure 7. Each mode is selected based on specific criteria like delivery urgency, geographical constraints, and package size. This integration allows for more efficient use of resources and faster delivery times, especially in densely populated urban areas where traditional delivery vehicles may face accessibility challenges.

[Diagram of multi-modal delivery network]

Figure 7. Flowchart for multi-modal delivery network.
These networks significantly reduce the carbon footprint of last-mile deliveries. Electric vehicles and bikes emit far fewer pollutants compared to traditional delivery trucks, aligning with the growing demand for eco-friendly logistics solutions. Drones, on the other hand, offer a zero-emission alternative for small package deliveries. This adaptability is particularly beneficial in cities with varying urban landscapes, allowing for flexible routing and delivery methods that can be tailored to specific environmental and infrastructural contexts.

The use of diverse transportation modes can lead to improved customer satisfaction by ensuring faster and more reliable deliveries. The backbone of these networks is advanced technology—incorporating AI for route optimization, real-time tracking systems for enhanced transparency, and automated sorting systems at local distribution centers. This technology integration ensures that each package is delivered through the most efficient route and method, enhancing the overall customer experience in e-commerce logistics.

Implementing predictive analytics using AI can dramatically improve route planning. By analyzing traffic patterns, weather conditions, and customer availability, deliveries can be scheduled more efficiently, reducing delays and increasing customer satisfaction. By analyzing extensive datasets, including historical traffic patterns, weather conditions, and consumer behavior, AI algorithms can predict the most effective delivery routes. This approach minimizes delays, reduces fuel consumption, and ensures timely deliveries, which are helpful for maintaining customer satisfaction and operational efficiency.

The use of predictive analytics allows for dynamic adaptation to changing conditions. It can reroute deliveries in real-time in response to unexpected traffic or weather changes, ensuring the fastest possible delivery times. This level of adaptability not only optimizes the delivery process but also significantly enhances customer satisfaction, as consumers receive their orders promptly and reliably.

5. Integration and Interoperability

In the realm of e-commerce logistics, ensuring a smooth transition of goods from their point of origin to the final destination is decisive. This requires a well-integrated system that allows for the efficient transfer of cargo between different modes of transport—maritime, air, and land. Furthermore, interoperability is essential to ensure that disparate systems and technologies can communicate and operate in harmony, which is vital for optimizing the entire supply chain, reducing delays, and enhancing the overall efficiency and reliability of e-commerce logistics.

System integration across different transport modes in e-commerce logistics is essential for a cohesive and efficient supply chain. This integration ensures that cargo is seamlessly transferred between maritime, air, and ground transportation, minimizing delays and maximizing efficiency. By leveraging technologies like IoT and unified communication protocols, logistics systems can synchronize operations across various modes, leading to a streamlined process that enhances the speed and reliability of deliveries from manufacturers to consumers [3,29,30]. This approach is helpful for meeting the rapid demands of e-commerce markets.

Real-time data sharing and effective communication protocols are important pieces of the e-commerce logistics puzzle for ensuring timely and efficient delivery. By utilizing advanced technologies like IoT and cloud-based systems, logistics networks can share essential data such as traffic conditions, weather updates, and package tracking in real-time. This immediate exchange of information enables dynamic routing and scheduling, significantly reducing delivery times and improving overall logistical efficiency. Effective communication protocols ensure that this diverse array of data is standardized and accessible across different platforms and stakeholders in the supply chain.

Interoperability in e-commerce logistics faces challenges such as varying technological standards and regulatory differences across regions. To overcome these challenges, solutions like establishing universal communication protocols and collaborative platforms are essential. These facilitate smooth data exchange and system compatibility, ensuring that different logistics components can work together effectively. Embracing open standards
and fostering partnerships among logistics providers, technology developers, and regulatory bodies can significantly enhance interoperability, leading to more efficient and unified global supply chain operations.

Artificial intelligence plays a great role in advancing interoperability across e-commerce logistics systems. AI facilitates the analysis and synthesis of data from diverse logistical components, enabling systems to anticipate supply chain disruptions and optimize operations. By learning from patterns and trends in data exchange, AI can improve decision-making processes, ensuring compatibility and efficiency across different logistics platforms [31]. This enhances the seamless integration of various transportation modes and logistical processes, fundamental for maintaining a fluid and responsive e-commerce supply chain.

Another aspect to take into consideration is the improvement of the efficiency and sustainability by synchromodal logistics, a dynamic and flexible approach to transportation. It emphasizes the seamless synchronization of different logistics activities and the integration of real-time information to enhance decision-making processes. The primary benefits of synchromodal logistics include increased flexibility, reduced transportation costs, and improved environmental sustainability.

Giusti et al. [32] discuss the critical success factors for implementing synchromodal logistics, emphasizing the importance of real-time information sharing and flexible shipment options to achieve optimal synchronization of logistics flows.

Smart steaming, a concept within synchromodal logistics, focuses on optimizing the speed and route of maritime vessels to reduce fuel consumption and emissions. Giusti et al. [33] demonstrate how smart steaming can contribute to more sustainable and cost-effective maritime transport by leveraging real-time data and advanced optimization techniques. This approach involves adjusting vessel speeds based on real-time information about weather conditions, port congestion, and cargo readiness, leading to significant reductions in fuel consumption and emissions. Integrating synchromodal logistics and smart steaming into our proposed system can enhance the overall efficiency, flexibility, and sustainability of e-commerce logistics.

6. Case Study: Possible Integration of Autonomous Systems in E-Commerce Logistics

In today’s globalized economy, e-commerce logistics not only demands efficiency and speed but also insists on sustainability and reliability. The proliferation of technological innovations, particularly in the realm of autonomous systems, offers unprecedented opportunities to enhance these aspects. This case study explores the end-to-end journey of a product, demonstrating how integrating autonomous technologies can revolutionize supply chains from production to delivery.

The primary objective of this case study is to illustrate a futuristic yet attainable model where autonomous systems—including trucks, ships, and drones—are seamlessly integrated to handle different segments of the logistics chain. By tracing a product’s journey from a factory in China to a customer in Romania, we aim to highlight the practical applications of these technologies and their collective impact on enhancing operational efficiencies, reducing environmental footprints, and improving overall customer satisfaction.

This case study follows the theoretical journey of a product from the production line to the final customer, divided into three stages:

1. Factory to Port in China (Autonomous Trucks);

The focus of this stage is on the utilization of autonomous trucks to transport goods from the factory to the maritime port, technologies enabling autonomous driving and its benefits, such as reduced labor costs and increased safety, and challenges, like regulatory compliance and integration with traditional vehicles.

2. Maritime Transport (Autonomous Shipping Vessel);

The second stage considered in the case study examines the transition of goods onto an ASV and the sea journey. It focuses on autonomous navigation and energy-efficient
propulsion systems, the environmental benefits of reduced emissions, and the operational challenges of ensuring safety and international regulatory compliance.

3. **Last-Mile Delivery in Romania (Drones and/or Autonomous Trucks to Drones)**

   - **Option 1:** Direct drone delivery from a central warehouse near the port to the customer, emphasizing rapid delivery and reduced environmental impact.
   - **Option 2:** Use of autonomous trucks for secondary distribution to multiple warehouses across Romania, followed by drone delivery to the final customer, enhancing logistics flexibility and coverage (as depicted in Figure 7).

**6.1. Stage 1: Factory to Port in China (Autonomous Trucks)**

The initial stage of the logistics chain involves the transportation of goods from a manufacturing site in China to the nearest maritime port. This segment utilizes autonomous trucks similar to ones produced by companies like Pony.ai, TuSimple or Einride, showcasing how cutting-edge autonomous driving technology transforms traditional truck logistics.

These trucks are equipped with advanced sensors, GPS, and AI-driven software that enable them to navigate roads independently, recognize traffic patterns, and make real-time driving decisions without human intervention [34]. Leveraging Vehicle-to-Everything (V2X) communication, autonomous trucks can communicate with other vehicles, infrastructure, and traffic systems to optimize route selection, avoid congestions, and enhance safety [35].

Autonomous trucks operate continuously without the need for breaks, reducing human error and decreasing the reliance on a human workforce, thus saving on labor costs. These trucks can operate 24/7, avoiding peak traffic times by traveling during off-peak hours, thus speeding up the transportation process and increasing logistical throughput.

By studying the latest advancements in autonomous trucks in China, it is evident that there has been significant progress in the development and commercial deployment of autonomous trucks. Companies have safely accumulated millions of kilometers of driving across China, which indicates not only technological readiness but also a regulatory environment that supports such advancements [36]. China’s rapid adoption of Levels 3 (L3) and Levels 2+ (L2+) autonomous heavy-duty trucks on public roads [37] showcases a regulatory landscape that is accommodating these technologies at scale.

Mastering the mass production of these systems and gaining buy-in from logistics companies will secure further development and demand increase. This implies a regulatory framework that supports both innovation and practical implementation in commercial settings, fostering an environment where autonomous driving technology can thrive.

Regarding interoperability, the key challenge is ensuring that autonomous trucks can safely coexist with traditional vehicles on public roads. The companies that develop autonomous vehicles are investing financial and human resources in the algorithms or safety protocols used to ensure interoperability. Autonomous vehicles use advanced sensing and machine learning algorithms to understand and predict the behaviors of human drivers, which helps prevent accidents and ensures smoother integration into existing traffic systems [34]. These systems are designed to react appropriately to unpredictable human driving patterns and adjust their operational strategies in real-time. Such technologies are necessary to ensure the safety and efficiency of autonomous trucks, especially during the transitional period when they share the roads with human-driven vehicles.

The regulatory landscape in China, as detailed in some resources [38,39], supports the deployment of autonomous vehicles by allowing extensive testing and by setting standards that encourage technological integration with existing logistics frameworks. This progressive regulatory approach, coupled with advanced technological solutions for interoperability, provides a robust framework for understanding how autonomous trucks are integrated into China’s transportation ecosystem.

The implementation strategy for autonomous logistics operations is built upon two foundational pillars: advanced route planning and energy efficiency. Route planning technology can incorporate artificial intelligence to analyze both historical traffic data and real-time traffic updates. This enables the autonomous trucks to identify and follow the
most efficient routes from the factory to the port, significantly minimizing delays and
ensuring that deliveries are consistently on schedule. Simultaneously, a strong emphasis
is placed on energy efficiency within these operations. The trucks can be equipped with
systems designed to optimize their driving patterns, effectively reducing fuel consumption
and operational costs. Furthermore, the incorporation of hybrid or electric trucks has the
potential to greatly enhance the sustainability of the logistics chain. Autonomous trucks,
especially those powered by electric or hybrid engines, significantly reduce emissions
compared to traditional diesel trucks. This not only aligns with global environmental goals
by lowering emissions but also boosts the overall efficiency of the transportation process.

This stage of the logistics chain demonstrates the potential of the technological ad-
vancements in autonomous vehicle technology and also highlights the practical applications
and benefits these systems offer in terms of efficiency, safety, and sustainability. As these
technologies continue to evolve and gain regulatory approval, they are set to revolutionize
the transport of goods, making logistics operations more efficient and environmentally
friendly. The successful implementation of autonomous trucks in China serves as a model
for global logistics operations, showcasing the potential for scalability and replication in
other regions and contexts.

6.2. Stage 2: Maritime Transport (Autonomous Shipping Vessel)

Following the efficient transition of goods via autonomous trucks, the next phase
involves leveraging Autonomous Surface Vessels (ASVs) managed by Ashore Operations
Centers (AOCs). This stage critically examines the potential and integration of ASVs and
AOCs in optimizing maritime transport operations.

Autonomous vessels, such as the envisioned MV Yara Birkeland, are equipped with
sophisticated sensors and AI-driven decision-making frameworks, enabling precise and
safe maritime navigation. These vessels independently navigate through complex shipping
lanes and congested maritime corridors, as described in Section 3 of the article.

Acting as the central network, the AOC provides overarching route management and
strategic guidance to ASVs. Utilizing high-resolution geospatial data and real-time envi-
ronmental feedback, AOCs dynamically optimize routes, mitigate navigational risks, and
ensure regulatory compliance, enhancing the interconnectedness of maritime operations.

The interactions between ASVs and AOCs are central to the proposed logistics archite-
cture. ASVs constantly communicate with AOCs, exchanging important data such as vessel
location, environmental conditions, and maritime traffic, thereby facilitating seamless and
efficient maritime operations.

The AOC acts as the onshore command center, providing overarching route manage-
ment and strategic guidance to ASVs. Using high-resolution geospatial data and real-time
environmental feedback, AOCs can optimize routes, foresee and mitigate potential naviga-
tional risks, and ensure regulatory compliance [24]. AOCs employ AI algorithms to adjust
ASV routes in real-time, enhancing fuel efficiency and minimizing navigational errors.
This integration not only improves operational efficiency but also promotes environmental
sustainability through optimized route planning.

Proposed ASVs incorporate energy-efficient propulsion systems, including electric
and hybrid options. These innovations significantly reduce emissions and align with global
sustainability goals, contributing to the emphasis on environmental efforts highlighted
in Section 3 of the paper. The energy-efficient technologies and route optimization strate-
gies underscore the potential for ASVs to reduce the maritime industry’s environmental
footprint substantially.

The deployment of ASVs involves navigating complex maritime regulatory envi-
ronments. Collaborative efforts with bodies like the International Maritime Organization
(IMO) are essential to evolve and adapt maritime laws to support autonomous technologies,
ensuring safety and compliance. Regular updates and compliance with the “framework for
the regulatory scoping exercise for the use of maritime autonomous surface ships (MASS)”
ensure legality and safety [40].
Integrating robust safety protocols and redundant systems within ASVs ensures operational safety and reliability. These measures are critical in transitioning to higher levels of maritime autonomy, as discussed in Section 3, which stresses the importance of safety in autonomous maritime operations.

As technology advances and regulatory environments mature, the broader deployment of ASVs coordinated by AOCs is expected to proliferate, further integrating autonomous technologies across global maritime logistics. This expansion will enhance the resilience and adaptability of maritime operations to meet global demands.

This stage highlights the transformative potential of integrating ASVs with AOCs in maritime transport. By enhancing operational efficiencies, ensuring high safety standards, and promoting environmental sustainability, this integrated approach exemplifies the advanced direction for global maritime logistics. The continuous evolution of regulatory standards and maritime technology, as articulated in Section 3 of the paper, will be essential in achieving unprecedented levels of automation and safety in maritime logistics.

6.3. Stage 3: Last-Mile Delivery in Romania

Upon the arrival of goods at the Romanian port, the final stage of our case study involves the implementation of last-mile delivery solutions. This stage examines two delivery options: direct drone delivery from a centralized warehouse near the port, and a two-step delivery process involving autonomous trucks to regional warehouses followed by drone delivery to customers.

6.3.1. Option 1: Direct Drone Delivery from Warehouse near the Port

Utilizing advanced drones equipped with GPS and collision avoidance systems, such as the ones developed by the Amazon Prime Air program, this option focuses on direct deliveries from a central warehouse near the port to the customer’s doorstep. Amazon’s MK30 drones are designed for high efficiency and can navigate urban and suburban environments autonomously [41].

Drones reduce delivery time dramatically by bypassing ground traffic and directly reaching consumers, thus enhancing the responsiveness of the e-commerce supply chain. Electric drones contribute significantly to reducing carbon emissions compared to traditional delivery vehicles, aligning with sustainable logistics practices as emphasized in the above sections of the article.

Managing airspace and ensuring privacy and safety are major challenges. Coordination with local aviation authorities and adherence to stringent safety protocols are necessary to mitigate risks and ensure public acceptance.

6.3.2. Current Regulatory Environment in Romania

Romania adheres to European Union regulations concerning Unmanned Aircraft Systems (UAS), notably Regulation (EU) 2019/945 and Regulation (EU) 2019/947. These regulations dictate the standards and operational guidelines for UAS, ensuring safety, privacy, and environmental protection. Romanian national laws, such as Law 21 on the Air Code and Government Decision HG 912/2010 concerning flight authorizations, also play a crucial role [42].

Amazon Prime Air utilizes sophisticated autonomous drones capable of delivering packages within an hour, designed to operate under varied and complex conditions. In contrast, Romania’s regulatory framework currently allows for the operation of UAS primarily in specified conditions under the “open” category with significant restrictions on flights over uninvolved persons and dense areas, limiting the possibility of extensive urban drone deliveries similar to Amazon Prime Air’s model.

According to Romanian regulations, UAS operations are highly regulated, especially regarding flight over populated areas and gatherings, where Amazon’s model aims for extensive use. Autonomous UAS, which operate without direct pilot intervention and can
react autonomously to unforeseen situations, are not yet permitted in open categories. This presents a significant barrier to implementing a service model like Amazon Prime Air.

To align Romania’s UAS regulations more closely with innovative delivery models like Amazon Prime Air, several adaptations are necessary:

- Romanian regulations will need to evolve to accommodate fully autonomous drones, which include capabilities for safe operation without direct human control, as demonstrated by Amazon Prime Air;
- Establishing a regulatory sandbox to allow for controlled, experimental UAS operations in urban areas could pave the way for comprehensive evaluation and integration of autonomous delivery drones;
- Continuous dialogue between UAS operators, regulatory bodies, and the public is essential to address safety, privacy, and efficiency concerns, facilitating a more flexible regulatory framework;
- Learning from EU advancements and international standards in UAS operations can help Romania accelerate its regulatory adaptations, ensuring safety and innovation go hand in hand.

The journey toward integrating advanced UAS delivery systems like Amazon Prime Air into Romanian logistics involves substantial regulatory updates and a shift in public perception. By carefully managing this transition, Romania can harness the potential of UAS technology to enhance its e-commerce and logistics sectors while ensuring compliance with safety and privacy standards. This adaptation not only aligns with technological advances but also supports the broader goal of sustainable and efficient logistics solutions.

6.3.3. Option 2: Two-Step Delivery—Autonomous Trucks to Regional Warehouses and Drones to Customers

This process involves using autonomous trucks to transport goods from the port to multiple regional warehouses across Romania. This setup aims to decentralize storage and reduce the distance for final deliveries. Drones then can take over from these warehouses to complete the last-mile delivery, ensuring that the final leg of the logistics chain is swift and efficient.

6.4. The Status of Autonomous Truck Legislation in Romania

In Romania, the regulatory approach toward autonomous vehicles, including trucks, is still in its early stages. A legislative draft aimed at establishing a framework for autonomous vehicle operations has been initiated but remains under review, indicating that the country is in the early phases of adapting its legal structure to accommodate these advanced technologies. This legislative effort reflects a proactive stance toward embracing autonomous transportation technologies, yet the absence of finalized laws presents a significant hurdle. For businesses and logistics operators, this uncertainty complicates planning and investment in autonomous truck fleets that could dramatically enhance logistical efficiency and safety. The advancement of this legislation would not only facilitate the integration of autonomous trucks into Romania’s transportation ecosystem but also position the country at the forefront of adopting innovative logistics solutions in Eastern Europe. Ensuring the successful passage and implementation of such a law will require concerted efforts among lawmakers, industry stakeholders, and the public to address safety concerns, technological standards, and liability issues associated with autonomous vehicle operations.

The two-step method increases the logistics network’s flexibility and coverage, making it possible to serve a broader area more effectively and reduce delivery times for remote regions. Like direct drone delivery, this option also focuses on minimizing the environmental impact. The use of autonomous trucks for longer intra-country hauls and drones for final delivery optimizes energy usage and reduces emissions. Advanced software integrates these delivery systems with e-commerce platforms, enabling seamless transition
of goods and real-time tracking for consumers, enhancing customer satisfaction and trust in e-commerce operations.

The combination of autonomous trucks and drones leverages the strengths of both technologies, where trucks handle bulk transport efficiently, and drones provide agile and precise delivery capabilities.

As technology advances and regulatory frameworks evolve, the scalability of these last-mile delivery options can be enhanced to include newer regions and integrate more advanced autonomous systems.

Future developments may include more sophisticated AI algorithms for better route optimization and even more energy-efficient drone models, further reducing the ecological footprint of last-mile deliveries.

The final stage of the logistics chain presents innovative last-mile delivery solutions that exemplify the use of autonomous technologies to enhance operational efficiency, customer satisfaction, and sustainability. Whether through direct drone deliveries from centralized warehouses or a comprehensive two-step delivery system involving autonomous trucks and drones, each method showcases the potential to transform e-commerce logistics into a faster, cleaner, and more efficient process. The continued integration and optimization of these technologies, guided by advancements in AI and regulatory developments, will shape the future of last-mile delivery in e-commerce, setting new standards for the industry worldwide.

6.5. Optimization Techniques in Autonomous Logistics

In addition to AI-based decision-making methods, we can also consider advanced optimization techniques to enhance the performance and efficiency of autonomous logistics systems. These techniques include:

1. Mixed-Integer Linear Programming (MILP): MILP is used for optimizing logistics operations such as facility location, route planning, and resource allocation. It helps in making strategic decisions that balance cost, efficiency, and sustainability. For example, one study [43] utilizes MILP to address the Synchronized Location–Trans-shipment Problem, ensuring optimal synchronization of logistics flows.

2. Genetic Algorithms (GA): GAs are employed for solving complex optimization problems by simulating the process of natural selection. They are particularly effective in scenarios with large search spaces and non-linear constraints. In our study, GAs are used to optimize the routing and scheduling of autonomous vehicles.

3. Stochastic Optimization: Stochastic optimization techniques are used to manage uncertainty and variability in logistics operations. These techniques incorporate probabilistic elements to account for uncertainties in supply and demand, travel times, and other operational factors. One paper [44] explores the application of stochastic optimization in strategic freight logistics planning, highlighting its effectiveness in managing uncertainties and enhancing resilience.

Managing uncertainty and stochasticity is crucial for the reliability and robustness of autonomous logistics systems. By incorporating stochastic optimization techniques, our proposed system can better handle variations in supply chain operations and improve overall performance. Giusti et al. [32] discuss the benefits of incorporating stochastic elements in logistics planning to enhance resilience and flexibility, providing valuable insights into managing uncertainties in logistics operations.

7. Challenges and Future Outlook

Integrating autonomous technologies into e-commerce logistics poses multifaceted challenges such as navigating complex regulatory environments, managing cybersecurity risks, and developing extensive infrastructure that supports these technologies. Additionally, the practical implementation of the proposed autonomous systems requires a forward-looking perspective, which underscores the need for a robust and adaptable infrastructure, streamlined legal frameworks, and advanced cybersecurity measures.
The implementation of autonomous logistics technologies faces significant regulatory challenges. These arise from the current lack of standardized legal frameworks and policies specifically tailored to autonomous operations, both in maritime and urban environments. The complexity increases when considering the international nature of e-commerce, where different countries have varied regulations. Addressing these challenges requires collaborative efforts to develop cohesive regulatory standards that support and safely govern the deployment of autonomous logistics technologies while ensuring international compliance and smooth operational integration.

The increase in system autonomy elevates the potential cybersecurity risks that could disrupt logistics operations. Ensuring the security of data and operational control systems is paramount. Strategies must include robust encryption methods, continuous monitoring, and the implementation of advanced security protocols to safeguard against unauthorized access and system breaches. In autonomous systems, but more pronounced in maritime transportation, cybersecurity threats and the corresponding countermeasures are paramount considerations. The threats range from communication system breaches to sensor manipulation, potentially compromising vessel operations. Effective countermeasures include advanced encryption, robust firewalls, and frequent security updates (see Figure 8) [45–48]. These measures are vital for protecting the integrity of vessel or port control systems and ensuring the safe navigation of autonomous ships in increasingly digital maritime environments.

Figure 8. Diagram that illustrates cybersecurity measures for autonomous transportation means.

Integrating security in the development phase is essential for autonomous maritime systems. This approach, known as “security by design,” involves embedding robust cybersecurity measures from the outset. It ensures that security is not an afterthought but a foundational component of the system’s architecture. This proactive stance in development helps to anticipate and mitigate potential vulnerabilities, safeguarding the system against emerging cyber threats and enhancing the overall safety and reliability of autonomous maritime operations.

For autonomous maritime systems, effective countermeasures against cybersecurity threats are critical. These include deploying multi-layered security protocols, regularly updating and patching software, and employing advanced encryption techniques to protect data transmissions. Additionally, implementing intrusion detection systems and conducting regular security audits are key for identifying and mitigating vulnerabilities. These countermeasures ensure the resilience of autonomous vessels against cyberattacks, maintaining their operational integrity and safeguarding maritime logistics networks.

Implementing autonomous logistics necessitates significant infrastructure upgrades. For ASVs, advanced port facilities equipped with automated docking and cargo handling systems are essential. In urban areas, infrastructure modifications are required to accommodate drone and robot deliveries, including designated launch and landing zones, and recharging stations. This infrastructure development is key to fully realizing the potential of autonomous delivery systems in both maritime and urban logistics.
Future technological advancements hold the promise of overcoming current limitations in autonomous logistics. Enhanced AI algorithms are expected to offer more sophisticated decision-making capabilities, improving the efficiency and safety of autonomous systems. Additionally, the development of more advanced sensors will provide better environmental perception, essential for autonomous vehicles’ navigation. These advancements will drive significant improvements in operational efficiency and safety for autonomous logistics systems.

The long-term benefits of autonomous logistics on sustainability are consistent. With increased efficiency and reduced reliance on manual processes, these systems offer a significant reduction in emissions, contributing to environmental preservation. Autonomous vehicles, particularly electric ones, and drones, are expected to be more energy-efficient, leading to a more sustainable use of resources. This shift toward autonomous logistics not only enhances operational efficiency but also aligns with global sustainability goals.

The arguments presented above highlight the need for collaborative efforts to develop standard legal frameworks, robust security measures, and extensive infrastructure development. Looking to the future, we need to move forward to the potential benefits of these technologies, particularly in enhancing efficiency and sustainability in e-commerce logistics. The focus is on how advanced AI and sensor technologies will drive improvements in operational safety and the significant environmental benefits of adopting autonomous logistics systems.

8. Conclusions

This study emphasizes the transformative role of autonomous logistics in e-commerce, from ground-based autonomous trucks to maritime and aerial drone deliveries, underscoring the role these technologies play in redefining the logistics landscape. It underscores the integration of AI and advanced sensor technologies, highlighting their critical impact on enhancing operational efficiency and sustainability. The research showcases how these innovations not only streamline logistics processes but also contribute significantly to environmental conservation.

The challenges identified, such as regulatory alignment, cybersecurity, and infrastructure development, are significant yet surmountable with sustained effort and continued innovation. Regulatory frameworks need to evolve in tandem with technological advances to support safe and efficient operations across different regions and industries. Similarly, robust cybersecurity measures are important to protect these highly interconnected systems from potential threats, ensuring reliability and trust in autonomous logistics solutions.

Moreover, the environmental benefits of adopting autonomous systems—highlighted through reduced emissions and optimized resource use—align closely with global sustainability goals, offering a greener alternative to traditional logistics methods. This shift not only supports ecological resilience but also enhances the economic efficiency of supply chains, providing a competitive edge to those who adopt these forward-thinking practices early.

In conclusion, the journey toward fully autonomous logistics is complex and faces many challenges but offers immense potential for innovation and improvement. As the case study and discussions within this paper show, the future of logistics lies in harnessing these advanced technologies to create more adaptable, efficient, and sustainable systems. Embracing this change will require ongoing collaboration among technologists, policymakers, and business leaders to find the path that leverages the strengths of autonomous technologies while addressing their inherent challenges.

Looking forward, the paper envisions a future where continuous technological advancements further revolutionize e-commerce logistics. This future vision includes more sustainable and efficient logistics practices, aligning with global environmental goals and reshaping the e-commerce landscape. The conclusions drawn underline the role of innovation in driving the next phase of logistics evolution.
Author Contributions: Conceptualization, N.A. and C.S.; methodology, N.A. and C.S.; validation, N.A., C.S. and A.I.; formal analysis, N.A. and C.S.; investigation, N.A. and C.S.; resources, N.A. and C.S.; data curation, N.A.; writing—original draft preparation, N.A.; writing—review and editing, N.A., C.S. and A.I.; visualization, N.A., C.S. and A.I.; project administration, N.A. and C.S.; funding acquisition, C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The raw data supporting the conclusions of this article are not readily available because are part of an ongoing study and will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

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