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Dynamic Routing and Scheduling Optimization for Cold Chain Vehicles in Vaccine Distribution Networks†

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Abstract

This paper explores to optimize dynamic routing and scheduling for cold chain vehicles in vaccine distribution networks. The paper focuses on providing sophisticated algorithms that can react to changes in real-time, realizing the importance of effective vaccination distribution for global health, especially during pandemics. These algorithms enable the timely and accurate distribution of medicinal goods that are sensitive to temperature changes by utilizing a combination of historical and real-time data along with predictive analytics. The proposed methodology includes a well-structured approach starting from data collection to algorithm development, simulation, and real-world testing. The integration of these technologies and algorithms into vaccine delivery networks holds significant potential for enhancing the effectiveness, economy, and security of logistics processes. The outcome of this research holds the potential to not just revolutionize cold chain logistics in the pharmaceutical industry, but also in a variety of industries, such as the food industry, where the integration of real-time data and predictive analytics, guarantees effective cold chain logistics while lowering operating costs and environmental effects.

Keywords: Cold chain logistics, Vaccine distribution networks, Dynamic routing algorithm, Scheduling optimization, Healthcare logistics, Machine learning

Introduction

In global healthcare, the effective distribution of vaccines is very important, especially given their vulnerability to temperature fluctuations. Maintaining an unbroken cold chain, where vaccines are kept at specific temperatures from production to administration - is critical for ensuring their potency and effectiveness. However, the existing methods of static routing and scheduling in vaccine distribution networks often fall short in adapting to dynamic challenges such as varying demand and unpredictable environmental factors (Sujaree & Samattapapong, 2021). These inefficiencies can lead to delayed deliveries, increased costs, and compromised vaccine quality. With the advent of advanced technologies like real-time data analytics and GPS tracking (Soori et al., 2023), there is a ripe opportunity to revolutionize vaccine distribution logistics. By developing dynamic routing algorithms and optimizing scheduling strategies, it is possible to enhance the efficiency of cold chain vehicles. This optimization not only ensures timely deliveries but also reduces operational costs and environmental impact. This research initiative aims to leverage these technologies to create innovative solutions, transforming vaccine distribution. Ultimately, this work holds the promise of significantly improving healthcare outcomes globally by ensuring the reliable and timely delivery of vaccines to all healthcare business stakeholders.

Current routing and scheduling methods in vaccine distribution networks illustrate significant gaps in adapting to dynamic factors such as varying demand, traffic conditions, and unpredictable environmental elements (Shukla et al., 2022). Traditional static approaches fail to address these challenges effectively, leading to delayed deliveries, increased operational costs, and compromised vaccine quality. These inefficiencies obstruct the timely and reliable distribution of vaccines, impacting public health initiatives on a global scale (ASHP Innovation Center, 2022).

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The importance of optimizing routing and scheduling practices cannot be overlooked. In addition, an efficient distribution of vaccines not only ensures timely access but also significantly reduces operational costs and minimizes the environmental footprint. Optimization, and leveraging real-time data and advanced algorithms are important for enhancing the efficiency of cold chain vehicles. By developing intelligent solutions, it is possible to improve delivery timelines, reduce expenses, and enhance the effectiveness of vaccine distribution networks, contributing to better healthcare outcomes. To address these gaps and optimize routing and scheduling processes. This study will focus on how to apply Dynamic Routing and Scheduling in vaccine distribution networks by proposing a theoretical algorithm framework, there are critical steps toward ensuring the seamless and effective distribution of vaccines, safeguarding their integrity and accessibility while promoting cost-efficiency and sustainability in healthcare logistics.

Literature review

Overview of cold chain logistics in the pharmaceutical industry

Supply Chain Management (SCM) is a critical aspect of any industrial sector, including the pharmaceutical industry. Active management of supply chain activities is essential for maximizing customer value and gaining a sustainable competitive advantage. This includes planning and execution of all stages involved - from sourcing and production to the delivery of the final product. Effective Supply Chain Management (SCM) ensures a seamless flow of goods, information, or services from suppliers to manufacturers, and from manufacturers to consumers. In the context of this paper, SCM will be discussed about the cold chain logistics of vaccine distribution. The optimization of routing and scheduling, which are core elements of SCM, can significantly increase efficiency and reliability in this sector.

Cold chain logistics is a vital component of the pharmaceutical industry to ensure the safe transport of temperature-sensitive products such as medicines. This is particularly critical for vaccines and drugs, which must maintain specific temperature ranges to preserve their efficacy. For vaccines, they must be kept within a specific temperature range, usually between 2 and 8 °C. The cold chain encompasses a series of processes including transportation, storage, and distribution, which are all carefully controlled to prevent temperature excursions (Duijzer et al., 2018). Hence, Cold chain logistics plays a pivotal role in maintaining product integrity from manufacturing facilities to end-users, ensuring the quality and safety of pharmaceuticals (ASHP Innovation Center, 2022). It is crucial to design a cold supply chain network that considers these challenges and incorporates appropriate solutions, such as alternative transportation modes and innovative storage and distribution methods (Saif & Elhedhli, 2016). The optimization of cold chain vehicles plays a significant role in the successful distribution of vaccines (Sujaree & Samattapapong, 2021). Optimizing the routing and scheduling of cold chain vehicles is key to ensuring the timely and efficient distribution of vaccines in temperature-controlled conditions. It helps minimize the risk of temperature excursions, reduces transportation costs, and improves overall logistics performance. Moreover, the use of advanced technologies and algorithms can help in dynamically adjusting routes and schedules based on real-time information such as traffic conditions, weather forecasts, and inventory levels (Soori et al., 2023).

Cold chain vehicles are equipped with temperature and humidity monitoring equipment that can effectively monitor and control the conditions during transportation, ensuring the integrity of the vaccines, (Zhao et al., 2023) have studied to test Temperature and Humidity Monitoring Equipment in the cold chain transportation process. Integrating real-time monitoring systems and advanced routing algorithms into cold chain vehicles can optimize the routes, which consider a factor such as temperature control, delivery time windows, traffic conditions, and delivery constraints (Sun et al., 2021).

Previous studies on routing and scheduling optimization

Several studies have explored the optimization of routing and scheduling in various contexts, not including pharmaceutical distribution. Khan et al. (2014) demonstrated the efficacy of dynamic routing algorithms in reducing transmission times and costs in mobile computer networks. Additionally, Thul and Powell (2023) proposed a heuristic scheduling approach that significantly improved resource allocation for vaccine and testing kits in the United States. Furthermore, Yeh and Tan (2021) highlights the need to consider vehicle type selection and route distribution in the optimization process, especially in scenarios with a heterogeneous fleet and time-varying speed models. However, dynamic routing and scheduling are essential in cold chain optimization for vaccine distribution networks. These processes consider real-time changes in factors such as weather conditions, traffic congestion, and vaccine demand. To our knowledge, there is little research conducted on Dynamic Routing and Scheduling Optimization for Cold Chain Vehicles in the specific context of vaccine distribution networks. For example, the optimization of cold chain logistics routes has been addressed (Jia, 2022). This study has explored the impact of transportation time on the quality of perishable goods and have developed optimization models and algorithms to find optimal routes in cold chain logistics for agricultural products. To improve the efficiency and quality of vaccine distribution networks, dynamic routing and scheduling optimization for cold chain vehicles need to be explored, and a optimization method model will be proposed to tackle this issue.

In a healthcare study conducted by (Yarmand et al., 2014), they used a stochastic optimization model to create a simulation that planned the allocation of seasonal influenza vaccines in different regions of North Carolina. The results showed a reduction in the attack rate and associated costs such as work loss, treatment, and hospitalization expenses due to prevented cases. Additionally, significant savings were observed in vaccine production and administration costs; however, the transportation of vaccines between regions was not taken into consideration. Amidst the global COVID-19 outbreak, Basciftci et al. (2021) propose a stochastic optimization approach to distributing vaccines and test kits in uncertain environments. This study presents various scenarios in the USA but does not specifically address vaccine delivery logistics in terms of cold chain vehicle routing or scheduling.

Technologies and algorithms utilized in dynamic routing

In recent years, advancements in technologies such as GPS tracking, Internet of Things (IoT) sensors, and machine learning algorithms have revolutionized dynamic routing. GPS tracking provides real-time vehicle location data, enabling route adjustments based on traffic patterns and unexpected delays. IoT sensors, on the other hand, offer live environmental data, crucial for ensuring the integrity of pharmaceuticals. Machine learning algorithms, as demonstrated by Soori et al. (2023), have shown promise in predicting optimal routes based on historical data, weather conditions, and demand fluctuations. These technologies empower real-time decision-making, leading to more responsive and adaptive routing strategies. Moreover, various optimization algorithms have been applied to dynamic routing and scheduling problems. These include but are not limited to genetic algorithms, ant colony optimization, simulated annealing, and tabu search. For example, Khan et al. (2014) implemented a routing algorithm based on a cluster mechanism in a problem of data distribution on a mobile computing network, where multiple mobile devices are using applications running in the same network domain. Furthermore, in the cloud computing system which is included more than thousands of computing nodes, Liu and Wang (2020) proposed the improved Genetic Algorithm called New Adaptive Genetic Algorithm (NAGA) to optimize a scheduling problem of cloud service resources with the result of reducing the total task execution time along with close to service quality of the cloud platform compared with previous service quality before implementing genetic algorithms. However, there are few studies on dynamic routing and scheduling in vaccine distribution networks.

The integration of dynamic routing technologies and algorithms in cold chain vehicle management within vaccine distribution networks has the potential to greatly enhance efficiency, and cost-effectiveness, and ensure reliable and safe logistics operations throughout the entire process. Therefore, the implementation of a dynamic routing and scheduling optimization algorithm for cold chain vehicles in vaccine distribution networks is an essential concept framework to ensure the timely and efficient delivery of vaccines.

Effective management of vaccine distribution systems is crucial to maintain the integrity of the cold chain and address challenges related to expiration, counterfeit products, and fraudulent records. One of the studies by Sun et al. (2009) applied game theory to allocate and distribute the vaccine stockpiles among different countries. Their theory advocates the decision-maker to contribute and coordinate their stockpiles with other countries in maintaining the epidemic during an outbreak. To enhance trust, transparency, traceability, and data management in global vaccine distributions, Yadav et al. (2023) propose integrating blockchain technology with IoT. However, implementing this solution may face obstacles due to required organizational changes and limited technical expertise. The research of Alromaih and Hassan (2022) explores a blockchain-based system called COVAC in Saudi Arabia. This system is specifically designed to handle the COVID testing and vaccination process for local organizations. They implement blockchain technology systems to ensure transparency, data integrity, and security in managing COVID-19 testing and vaccination records. However, it also suggests the importance of developing additional tools using alternative techniques to handle data efficiently in the healthcare sector.

Challenges and solutions in cold chain vehicle optimization

The field of operations management has shown increasing interest in the logistical aspects of vaccine distribution. Duijzer et al. (2018) classified the vaccine supply chain into 4 components - product, production, allocation, and distribution - and analyzed decision problems for different types of outbreaks in developing and developed countries. They identified key characteristics such as high uncertainty in both supply and demand, decentralized decision-making between stakeholders, and the importance of timely decisions. With vaccines becoming more accessible in developing countries, there are opportunities to leverage logistics expertise to ensure efficient medical delivery without constraints caused by logistical issues. Markhorst et al. (2021) present a Decision Support System (DSS) optimization model to enhance the capacity planning to allocate vaccines for the COVID-19 vaccination process in the Netherlands. The DSS is ideally suited for providing support in a dynamic environment such as the availability of vaccines of different types, changes in supply, and the availability of healthcare professionals. However, the DSS model has some limitations on the fixed distances between the medical center and the vaccine hub since the actual travel distance might be excess or lower, and another limitation was not considering the cost of opening a vaccine hub because these costs were unknown.

Challenges in cold chain vehicle optimization include unpredictable temperature conditions, varying demand, and the need for strict adherence to regulatory standards. Some researchers (Saif & Elhedhli, 2016) have proposed innovative solutions to address these challenges. They used a novel hybrid simulation-optimization approach to solve the cold supply chain delivery problem for publicly-funded vaccines in Ontario, in this hypothetical case, the result shows no increase in cost with this proposed can be tailored for many real-life situations for instance different patterns of demands, inventory policies, transportation channels, and operational constraints. Additionally, regulatory compliance solutions, such as the integration of blockchain technology which provides transparent and immutable records, ensuring adherence to quality standards and regulations in each country need to be considered. This challenge is related to Smorgunov (2020) studies on public government ability in the context of digitalization because blockchain is oriented towards procedural justice, this is one of the concepts of “co-creation” and “co-production” which has been applied in political science, public administration on new digital public administration platforms to ensure co-production in public policy is affordable with such basic norms that encourage citizen participation open, fair, and reasonable.

Based on the literature reviews, an issue related to the optimization in the cold chain distribution and vehicle routing problem is the static routing and scheduling because the studies use specific conditions to generate the optimization model such as facility locations, customer demand, the limitation capacity of vehicles, the number of vehicles in the distribution center, and a fixed time for loading and unloading product at the destination, which are known or fixed. For example, some studies refer to the use of the same type of refrigerated vehicles to distribute a single product to customers through a single distribution center (Zhu & Zhou, 2019). Another example is that the required product is serviced by one vehicle rather than combined with various products from the same vehicle (Sujaree & Samattapapong, 2021). However, the extant literature has seldom considered dynamic conditions such as a temperature change over time outside of the refrigerated vehicle during vehicle transportation, traffic congestion, and a vehicle journey speed at the same time (Wang et al., 2017). Therefore, it is proposed that there is a need to fill the gap by applying the real-time data to generate an optimization model for cold chain vehicles in Vaccine Distribution Networks to make the model more realistic. This was mentioned by Soori et al. (2023) that the use of

Artificial Intelligence (AI), Machine Learning (ML) and Deep Learning (DL) algorithms can analyze traffic congestions and optimize vehicle routes as well as identify potential hazards and alert drivers in real-time.

Therefore, the current understanding leads to the following research objective on how to enhance the efficiency of cold chain vehicles in vaccine distribution networks by leveraging real-time data analytics, varying temperature conditions, and traffic environments in the delivery process for vaccine distribution.

This research is planned to develop an algorithm framework for optimizing the routing and scheduling of cold chain vehicles in vaccine distribution networks, considering the unique requirements of unpredictable temperature conditions, fluctuating demand, vehicle transport conditions, and regulatory compliance. This algorithm will aim to minimize transportation costs, reduce the risk of temperature excursions, and improve overall logistics performance in the healthcare sector.

Methodology

This study is to present a structured approach for data collection, algorithm development, simulation, and real-world testing. By combining historical data analysis, advanced algorithm design, simulation studies, and practical validation, the research aims to create a robust and adaptable solution for dynamic routing and scheduling optimization in pharmaceutical cold chain logistics. The proposed methodology involves the following steps.

Data collection

There are 3 major milestones in data collection.

Defining data requirements and establishing data sources: To begin with clearly outlining the specific data needed, then encompassing historical distribution routes, delivery schedules, temperature records, geographic locations, traffic patterns, and incidents of temperature excursions. Then, determine the timeframe for data collection while simultaneously identifying relevant sources, including pharmaceutical companies, distributors, healthcare facilities, regulatory bodies, meteorological agencies, and transportation authorities. Obtain necessary permissions and agreements for data sharing to ensure seamless access to vital information.

Collecting historical distribution data, gathering geographic and environmental data, and conducting surveys: First, gather past distribution data from distributor agents and pharmaceutical companies, transportation routes, delivery schedules, vehicle types, and instances of temperature fluctuations. Simultaneously, utilize Geographic Information Systems software to create visual distribution network maps, incorporating urban density, road systems, healthcare facilities, and potential congestion areas. Next, is to collect historical weather data, focusing on temperature variations and extreme weather events, to comprehensively understand environmental factors. Then, engage key stakeholders such as logistics managers, drivers, warehouse staff, and healthcare facility personnel through surveys and interviews. Extract qualitative insights on challenges faced in cold chain logistics, thus enriching the dataset with knowledge experiences.

Deploying IoT sensors and GPS tracking, analyzing regulatory documents, organizing focus group discussions, validating data accuracy, and documenting data collection procedures: These steps are to implement IoT sensors in vehicles for real-time monitoring of temperature and other relevant factors. Concurrently, employ GPS tracking devices to collect live location data, facilitating in-depth analysis of routes and deviations. Then, review pharmaceutical cold chain logistics regulations and standards, comprehending the compliance benchmarks set by regulatory authorities. Organize focused discussions with logistics experts, technology providers, and regulatory authorities to explore challenges, best practices, and innovations in the field. Finally, to ensure data accuracy by cross-verifying information from multiple sources, conducting data cleansing, and addressing inconsistencies or missing points. Additionally, maintain meticulous records detailing data collection methods, sources, and transformations applied, fostering transparency and traceability throughout the research process.

Algorithm development

This paper delves into several critical facets of algorithm development tailored to this unique context.

Understanding the problem domain: Firstly, a thorough understanding of cold chain logistics is essential to creating algorithms. This knowledge encompasses pharmaceutical transportation regulations, geographical complexities, real-time data sources, and the specific requisites of temperature-sensitive vehicles. Another step is to grasp the intricacies of the problem, algorithms can be designed to precisely meet the distinctive demands of cold chain logistics.

Dynamic routing and scheduling optimization: This is a pivotal aspect that involves the utilization of dynamic routing algorithms, which calculate optimal routes for vehicles in real-time, factoring in variables like traffic conditions, road closures, weather events, and delivery schedules. Applying the potential machine learning techniques, such as reinforcement learning and neural networks, are harnessed, then leveraging historical and real-time data for accurate predictions. Concurrently, scheduling algorithms optimize task assignments, employing techniques like Genetic Algorithms and Ant Colony Optimization. These algorithms meticulously consider vehicle capacity, delivery time windows, geographic constraints, and demand patterns, maximizing resource usage, minimizing costs, and ensuring punctual deliveries.

Real-time Data Integration, Predictive Analytics, and Iterative Refinement: First, integrating real-time data from GPS devices, IoT sensors, and live weather updates is integral. Next, to process this flood of data quickly, algorithms are carefully designed. Then, machine learning models are trained using both historical and real-time data to predict future events, enabling proactive route adjustments and optimized scheduling. Predictive analytics models forecast demand patterns and potential disruptions, aiding proactive resource allocation. Next, thorough testing using simulation software and a variety of scenarios is imperative. Finally, real-world testing with live data further validates algorithm effectiveness under various conditions. This iterative process incorporates feedback from testing, allowing continuous refinement. Hence, machine learning models are retrained with new data, enhancing their predictive accuracy. To that end, regular updates ensure algorithms remain adept in handling evolving challenges within cold chain logistics, ensuring the efficient, reliable, and timely transportation of temperature-sensitive pharmaceutical products.

Simulation and testing

The simulation and testing process includes detailed explanations of the procedures that are followed.

1) Utilization of Simulation Software for Testing the Developed Algorithm

In the testing phase, simulation software like AnyLogic or Arena is employed to create virtual models of the pharmaceutical supply chain and cold chain logistics network. These simulations replicate real-world scenarios, incorporating elements such as distribution centers, transportation routes, weather conditions, and demand patterns. Various scenarios, including peak demand periods, adverse weather events, traffic congestion, and supply chain disruptions, are modelled to assess the algorithms' performance under specific challenges. The developed dynamic routing algorithms and scheduling optimization techniques are implemented within the simulation, enabling real-time decision-making and route adjustments based on simulated conditions. Historical and real-time data, encompassing temperature records, traffic patterns, and demand fluctuations, are integrated to provide algorithms with essential inputs for informed decision-making. Key performance metrics like delivery time, vehicle utilization, on-time delivery rate, and temperature stability are defined and utilized to evaluate the algorithms' effectiveness across diverse simulation scenarios.

2) Real-world Testing and Validation

In the real-world testing and validation phase, the optimized algorithms are put into action within actual cold chain logistics operations, utilizing vehicles equipped with GPS tracking, IoT sensors, and the implemented algorithms for pharmaceutical deliveries. Real-time data, including route adherence, temperature stability, and delivery accuracy, is collected from these field tests. In this phase, a healthcare or pharmaceutical organization need to be considered as a case study. This real-world data is then rigorously compared with the results derived from simulation scenarios, allowing for a comprehensive comparative analysis that validates the accuracy and reliability of the algorithms. Then, discrepancies between simulated outcomes and real-world results are meticulously investigated and utilized to refine the algorithms. Additionally, qualitative feedback from stakeholders involved in the real-world testing, such as drivers, warehouse staff, and logistics managers, is gathered for analysis. These insights provide valuable qualitative feedback on the algorithms' usability and effectiveness in practical scenarios, driving iterative refinements. Based on real-world testing outcomes, algorithms are continuously refined, including potential retraining of machine learning models and adjustment of algorithm parameters, ensuring consistent high efficiency and reliability both in simulations and real-world operations.

Simulation and real-world testing are essential for validating the developed algorithms. These methods allow researchers to evaluate the adaptability, responsiveness, and accuracy of the algorithms in dealing with various complexities of cold chain logistics. This ensures that they meet the requirements of pharmaceutical transportation in different dynamic environments.

Results and discussion

This study can make a valuable contribution to the field of optimizing cold chain logistics in vaccine distribution networks. By utilizing advanced algorithms for dynamic routing and scheduling optimization, this research aims to enhance the efficiency and effectiveness of vaccine distribution in cold chain logistics. The potential impacts include but are not limited to.

Firstly, the implementation of advanced algorithms for dynamic routing and scheduling optimization continued to improve healthcare access by ensuring timely and reliable vaccine deliveries, particularly crucial during emergency circumstances like the COVID-19 pandemic. The research by Markhorst et al. (2021) proposed the optimization model of the so-called Decision Support System (DSS) also can assist policymakers in achieving a better understanding of the possible consequences of the resource's allocation for example vaccines, vaccination capacity, and a number of the medical center with the need of integration of real-time dynamic routing and scheduling environment. This efficiency contributes to enhanced public health outcomes by minimizing delays and maintaining vaccine potency, thus reducing disease prevalence and healthcare burdens, ultimately fostering healthier communities. According to the World Health Organization, access to vaccines is crucial in achieving Universal Health Coverage (Almulhim & Barahona, 2023) and is a part of the primary Sustainable Development Goals (Griggs et al., 2013). Moreover, the research offers substantial cost-efficiency and resource optimization by reducing operational costs, including fuel consumption, vehicle wear, and labour hours (Yarmand et al., 2014). These savings are pivotal for healthcare budgets, allowing allocation to other vital areas of public health. The research aligns with the findings of Wang et al. (2017), suggesting that optimizing cold chain logistics can decrease operational costs, including fuel, maintenance, and personnel expenses. Additionally, the study promotes sustainability and environmental conservation by minimizing unnecessary transportation, thereby reducing emissions and fuel usage (Saif & Elhedhli, 2016). This aligns with global efforts to combat climate change, fostering greener and more sustainable healthcare supply chains. Badruddin (2023) mentions this stainability and environmental conservation will contribute to the United Nations Environment Programme (2020).

Conclusions

This paper focuses on the development and optimization of algorithm frameworks for dynamic routing and scheduling in cold chain logistics, specifically tailored for the pharmaceutical industry. The paper outlines a comprehensive approach, including data collection, algorithm development, and rigorous testing methods to enhance the efficiency and reliability of vaccine distribution networks. By integrating real-time data, predictive analytics, and advanced optimization techniques, the proposed algorithms aim to adaptively respond to changing conditions, ensuring on-time deliveries and the integrity of temperature-sensitive pharmaceutical products in optimal conditions.

The significance of this study lies in its potential to revolutionize cold chain logistics within the pharmaceutical industry. Efficient vaccine distribution is critical for global health, especially during times of pandemic. The Optimized routing and scheduling algorithms can minimize delays, reduce operational costs, and enhance the overall resilience of the supply chain. The potential benefits of implementing these algorithms include improving healthcare access by ensuring timely and reliable vaccine deliveries, particularly crucial during emergency situations like pandemics. This effectiveness supports improved public health outcomes, which in turn helps policymakers and decision-makers plan and manage the vaccination resource to satisfy demand and respond promptly to necessary actions, resulting in minimizing the patient's risk of mortality.

The implications of this research will extend far beyond the scope of the current study, which can be applied in real-world scenarios to improve healthcare outcomes. Successful implementation of the proposed algorithms could lead to widespread adoption in the pharmaceutical industry, impacting not only vaccine distribution but also the transportation of other temperature-sensitive medications with competitive advantages such as logistics cost reduction, maintaining vaccine quality and customer satisfaction. Furthermore, the techniques and algorithms created in this work can be used as a model for supply chain optimization in a variety of industries, such as the food industry, where perishable products are involved. Logistics procedures will change as a result of the integration of real-time data and predictive analytics, guaranteeing the effective flow of goods while lowering operating costs and environmental effects.

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