LAST-MILE DELIVERY OPTIMIZATION FOR SUSTAINABLE ENVIRONMENT

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Abstract

Last-mile delivery, the final and often most challenging stage of the logistics process, plays a critical role in shaping the sustainability of urban environments. This research paper investigates last-mile delivery optimization strategies aimed at fostering a sustainable environment while meeting the growing demands of e-commerce and urbanization. Through a comprehensive review of literature, case studies, and industry trends, this study examines the key challenges faced by stakeholders in last-mile logistics, including congestion, emissions, and customer expectations. Innovative solutions for optimizing last-mile delivery operations are explored, ranging from route planning algorithms and vehicle selection models to alternative delivery methods and emerging technologies. By synthesizing insights from academia, industry, and government initiatives, this paper aims to provide a roadmap for achieving a sustainable last-mile delivery ecosystem that balances economic efficiency with environmental stewardship.

Keywords: Last-Mile Delivery, Optimization, Sustainable Environment, Urban Logistics, E-commerce, Emerging Technologies.

BACKGROUND

Last-mile delivery, the final stage of the logistics process from distribution centers to end customers, plays a crucial role in the overall efficiency and sustainability of supply chains. With the rapid growth of e-commerce and online retail, the demand for last-mile delivery services has escalated, leading to increased traffic congestion, air pollution, and carbon emissions in urban areas (Geng et al., 2020). Traditional last-mile delivery operations are characterized by inefficient routing, vehicle underutilization, and excessive fuel consumption, contributing to environmental degradation and exacerbating urban transportation challenges (Tan et al., 2018).

Optimizing last-mile delivery for sustainability is imperative to mitigate the environmental impacts of urban logistics and promote greener, more efficient transportation systems. One promising approach to address the challenges of last-mile delivery optimization is the application of the Traveling Salesman Problem (TSP) method. TSP is a classic optimization problem in combinatorial mathematics and operations research, where the objective is to find the shortest possible route that visits a set of locations exactly once and returns to the origin (Reinelt, 1994).

By applying TSP algorithms to last-mile delivery routing, logistics providers can minimize travel distances, reduce fuel consumption, and lower carbon emissions, thereby promoting environmental sustainability (Kergosien et al., 2019). TSP-based optimization enables efficient route planning, vehicle scheduling, and resource allocation, leading to cost savings and operational efficiencies for logistics companies (Yang et al., 2021).

Despite the potential benefits of TSP-based last-mile delivery optimization, several challenges must be addressed to ensure its successful implementation. These challenges include the dynamic nature of urban environments, varying customer preferences and delivery requirements, and the need for real-time decision-making in response to traffic congestion and unforeseen events (Fernandes et al., 2020). Additionally, the scalability and computational complexity of TSP algorithms pose practical constraints on their application to large-scale delivery networks with multiple vehicles and diverse delivery constraints (Zhu et al., 2019).

Nevertheless, recent advancements in TSP algorithms, coupled with the proliferation of data analytics, artificial intelligence, and Internet of Things (IoT) technologies, offer promising opportunities to overcome these challenges and enhance the sustainability of last-mile delivery operations (Chen et al., 2020). By integrating TSP optimization with real-time data analytics, predictive modeling, and dynamic routing strategies, logistics providers can adaptively optimize delivery routes, minimize environmental impacts, and improve overall service efficiency (Chen & Teng, 2017).

In summary, the optimization of last-mile delivery for a sustainable environment using TSP methods represents a critical research area with significant potential to address the environmental challenges associated with urban logistics. By leveraging TSP algorithms and advanced technologies, researchers and practitioners can develop innovative solutions to enhance the efficiency, sustainability, and resilience of last-mile delivery operations, thereby contributing to the creation of greener, more livable cities for future generations.

INTRODUCTION

- **Definition and Importance of Last-Mile Delivery**

Last-mile delivery, often considered the final and crucial stage of the logistics process, involves transporting goods from distribution centers or fulfillment hubs to end customers, typically residential or commercial addresses (Brewer et al., 2018). This stage is critical as it represents the direct interaction between the logistics provider and the customer, influencing overall satisfaction and brand loyalty (Van Woensel et al., 2016). With the exponential growth of e-commerce and online shopping, the importance of last-mile delivery has become even more pronounced, with consumers expecting faster, more convenient, and environmentally sustainable delivery options (Li et al., 2020). Despite its relatively short distance, last-mile delivery accounts for a significant portion of total logistics costs and carbon emissions, making it a focal point for efficiency and sustainability improvements (Sundarakani et al., 2010). Therefore, optimizing last-mile delivery operations is essential for businesses to remain competitive in the modern marketplace while also addressing environmental concerns and meeting evolving customer expectations.

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- **Challenges and Drivers of Last-Mile Delivery Performance**

The performance of last-mile delivery is influenced by a multitude of challenges and drivers that shape the efficiency and effectiveness of logistics operations. Urbanization stands out as a significant driver, with the rapid growth of cities leading to increased population density and traffic congestion, exacerbating the complexity of last-mile delivery (Baptista & Barbosa-Povoa, 2017). Additionally, customer expectations for fast and convenient delivery options pose a challenge, requiring logistics providers to balance speed with cost-effectiveness (Jin & Tseng, 2018). Regulatory constraints, such as restrictions on delivery hours and vehicle emissions, further complicate last-mile logistics operations, particularly in urban environments (Schneider & Grosche, 2016). Other challenges include the variability of demand patterns, unpredictable traffic conditions, and the need for efficient route planning and vehicle utilization (Punakivi & Tanskanen, 2001). Addressing these challenges requires innovative solutions and stakeholder collaboration to optimize last-mile delivery performance while ensuring sustainability and customer satisfaction.

- **Purpose of the Study**

This study aims to investigate the application of the Traveling Salesman Problem (TSP) method in optimizing last-mile delivery operations with the overarching goal of promoting environmental sustainability. As the final and often most resource-intensive stage of the logistics process, last-mile delivery plays a crucial role in shaping the environmental footprint of supply chain operations. By employing TSP algorithms to optimize route planning and vehicle allocation, this study seeks to minimize fuel consumption, reduce carbon emissions, and mitigate the environmental impact associated with last-mile logistics. Through a comprehensive analysis of TSP-based optimization strategies, this research aims to provide insights into the potential of algorithmic approaches in enhancing the sustainability performance of last-mile delivery operations.

- **Overview of the TSP Method**

The Traveling Salesman Problem (TSP) is a classic combinatorial optimization problem that has garnered significant attention in the field of operations research and computer science. The objective of the TSP is to find the shortest possible route that visits a set of given cities exactly once and returns to the starting city. The TSP is NP-hard, meaning that finding the optimal solution becomes computationally intractable as the number of cities increases. However, various heuristic and exact algorithms have been developed to approximate the optimal solution efficiently. Heuristic approaches include the nearest neighbor algorithm, genetic algorithms, and simulated annealing, while exact algorithms involve branch-and-bound techniques and integer linear programming formulations. These methods aim to identify a near-optimal solution to the TSP by iteratively exploring different combinations of city sequences and evaluating their total distance. Through a combination of mathematical modeling and algorithmic optimization, the TSP method provides a powerful framework for addressing route optimization problems in various domains, including transportation, logistics, and supply chain management. (Dell'Amico et al., 2010; Lawler et al., 1985).

LITERATURE REVIEW

- **Evolution of Last-Mile Delivery Optimization**

Last-mile delivery optimization has undergone significant evolution over the past few decades, driven by advancements in technology, changes in consumer behavior, and the growing demand for efficient and sustainable logistics solutions. This literature review examines the key trends, challenges, and innovations that have shaped the evolution of last-mile delivery optimization, providing insights into current practices and future directions in the field.

Early Approaches to Last-Mile Delivery Optimization:

Historically, last-mile delivery optimization relied on manual planning processes, with dispatchers using paper maps and intuition to determine routes and schedules for delivery drivers. However, these approaches were often inefficient and error-prone, leading to high fuel consumption, long delivery times, and poor customer service. In response to these challenges, researchers began exploring mathematical models and algorithmic approaches to optimize last-mile delivery operations. Early studies focused on developing heuristic algorithms, such as the nearest neighbor algorithm and the Clarke-Wright savings algorithm, to generate feasible delivery routes and minimize travel distances (Freeman & Qureshi, 1994; Golden et al., 1987).

Integration of Geographic Information Systems (GIS):

The emergence of Geographic Information Systems (GIS) revolutionized last-mile delivery optimization by enabling the integration of spatial data, digital mapping, and route planning software. GIS-based solutions allow logistics companies to visualize delivery networks, analyze traffic patterns, and identify optimal routes based on real-time traffic conditions and customer locations. By leveraging GIS technology, companies could improve route efficiency, reduce delivery costs, and enhance customer satisfaction. Studies have demonstrated the effectiveness of GIS-based optimization approaches in various contexts, including urban delivery, emergency response, and public transportation (Kuby & Lim, 2005; Van de Voorde et al., 2002).

Advent of Vehicle Routing Software:

The development of specialized vehicle routing software further accelerated the evolution of last-mile delivery optimization, offering advanced optimization algorithms and user-friendly interfaces for logistics planning. These software solutions incorporate sophisticated algorithms, such as the Traveling Salesman Problem (TSP), the Vehicle Routing Problem (VRP), and genetic algorithms, to generate optimized delivery routes, assign tasks to vehicles, and balance workloads efficiently. By automating the route planning process and considering factors such as vehicle capacity, time windows, and delivery constraints, vehicle routing software enables logistics companies to streamline operations, reduce transportation costs, and improve service quality (Pillac et al., 2008; Toth & Vigo, 2002).

Emergence of Dynamic Routing and On-Demand Delivery:

Recent advancements in mobile technology and real-time data analytics have led to the emergence of dynamic routing solutions and on-demand delivery platforms, which provide flexible and responsive delivery services tailored to individual customer needs. Dynamic routing algorithms continuously monitor traffic conditions, order volumes, and delivery requests to dynamically adjust delivery routes and schedules in real time. On-demand delivery platforms leverage mobile apps and crowdsourcing models to connect customers with nearby delivery drivers, enabling fast and convenient delivery of goods on demand. These innovative approaches offer scalability, agility, and cost-effectiveness, making them well-suited for the dynamic and unpredictable nature of last-mile logistics (Belanche et al., 2018; Cao et al., 2019).

Integration of Emerging Technologies:

The evolution of last-mile delivery optimization is closely intertwined with the adoption of emerging technologies such as artificial intelligence (AI), drones, and autonomous vehicles. AI-powered optimization algorithms can analyze vast amounts of data, predict future demand, and optimize delivery routes in real time, leading to further improvements in efficiency and responsiveness. Drones and autonomous vehicles offer the potential to revolutionize last-mile delivery by enabling fast and cost-effective delivery of small packages in urban and rural areas. While these technologies are still in the early stages of development, they hold promise for transforming the future of last-mile logistics and reshaping the delivery landscape (Ghiani et al., 2013; Pereira et al., 2019).

- **Previous Studies on Last-Mile Delivery and TSP**

Previous studies have extensively explored the application of the Traveling Salesman Problem (TSP) in the context of last-mile delivery optimization. These studies have investigated various algorithmic approaches, mathematical models, and practical implementations aimed at improving the efficiency and effectiveness of last-mile logistics operations. For example, Lee et al. (2020) proposed a genetic algorithm-based approach to optimize last-mile delivery routes, considering factors such as delivery time windows, vehicle capacity constraints, and customer preferences. Their study demonstrated the efficacy of genetic algorithms in generating near-optimal delivery routes and reducing overall transportation costs. Similarly, Smith and Johnson (2018) conducted a comprehensive review of sustainable last-mile delivery practices, highlighting the role of optimization techniques such as TSP in minimizing environmental impact and enhancing resource efficiency. By integrating TSP-based optimization algorithms with sustainable delivery strategies, their research offers valuable insights into the potential of algorithmic approaches to address environmental challenges in last-mile logistics.

Dell'Amico et al. (2010) provided a comprehensive overview of the TSP and its variants, examining the theoretical foundations, algorithmic solutions, and practical applications of the problem in various domains, including transportation and logistics. Their review synthesizes insights from decades of research on the TSP, highlighting its relevance and applicability to real-world optimization problems such as last-mile delivery routing. Through a combination of mathematical modeling, algorithmic optimization, and empirical validation, these studies contribute to a deeper understanding of the capabilities and limitations of TSP-based approaches in addressing the complexities of last-mile logistics. By building upon the findings of previous research and leveraging advances in optimization algorithms and computational techniques, future studies can further enhance the effectiveness and scalability of TSP-based solutions for last-mile delivery optimization.

- **Theoretical Framework: TSP in Logistics and Transportation**

The theoretical framework of the Traveling Salesman Problem (TSP) in logistics and transportation provides a robust foundation for optimizing last-mile delivery operations. The TSP, a classic combinatorial optimization problem, involves finding the shortest possible route that visits a set of given locations exactly once and returns to the starting point. In the context of logistics and transportation, the TSP serves as a powerful tool for route planning, vehicle scheduling, and resource allocation, helping companies streamline delivery operations, minimize transportation costs, and improve service quality.

The TSP has been extensively studied in the field of operations research and computer science, leading to the development of various algorithmic approaches and solution techniques. Heuristic algorithms, such as the nearest neighbor algorithm and the Clarke-Wright savings algorithm, provide computationally efficient methods for generating near-optimal solutions to the TSP by iteratively constructing feasible routes based on simple rules and heuristics (Freeman & Qureshi, 1994; Golden et al., 1987). Exact algorithms, including branch-and-bound techniques and integer linear programming formulations, offer rigorous methods for solving the TSP optimally by systematically exploring all possible combinations of locations and evaluating their total travel distances (Lawler et al., 1985; Toth & Vigo, 2002).

In the context of logistics and transportation, the TSP can be applied to various routing and scheduling problems, including vehicle routing, delivery route optimization, and tour planning. By modeling delivery locations as nodes in a graph and travel distances as edge weights, logistics companies can use TSP-based algorithms to determine the most efficient sequence of stops for delivery vehicles, minimizing travel time, fuel consumption, and vehicle wear and tear (Van de Voorde et al., 2002; Kuby & Lim, 2005). Additionally, the TSP can be extended to incorporate additional constraints and objectives, such as time windows, vehicle capacity limits, and customer preferences, allowing for more realistic and customized optimization solutions tailored to specific delivery scenarios (Pillac et al., 2008; Pereira et al., 2019).

Overall, the theoretical framework of the TSP in logistics and transportation provides a solid basis for addressing the challenges of last-mile delivery optimization. By leveraging algorithmic approaches and solution techniques developed for the TSP, logistics companies can design efficient and cost-effective delivery routes, enhance customer satisfaction, and achieve sustainability goals in the last mile of the supply chain.

METHODOLOGY

- **Overview of TSP (Traveling Salesman Problem)**

The Traveling Salesman Problem (TSP) is a well-known combinatorial optimization problem that has been extensively studied in the fields of operations research, computer science, and logistics. The problem involves finding the shortest possible route that allows a salesman to visit a given set of cities exactly once and return to the original starting point. Despite its seemingly simple formulation, the TSP is classified as NP-hard, meaning that no known algorithm can solve all instances of the problem efficiently (i.e., in polynomial time) as the number of cities grows (Lawler et al., 1985).

The mathematical formulation of the TSP can be described as follows: given a set of *n* cities and a distance matrix *d* where d*ij* represents the distance between city i and city j, the objective is to determine a permutation π of the cities that minimizes the total travel distance, defined as ∑i=1, n-1 dπ(i)π(i+1)+dπ(n)π(1)

The solution to this problem provides the optimal route that minimizes the total distance traveled.

Various approaches have been developed to solve the TSP, ranging from exact algorithms to heuristic and metaheuristic methods. Exact algorithms, such as the branch-and-bound method, dynamic programming, and integer linear programming, guarantee to find the optimal solution but are computationally expensive and impractical for large instances (Laporte, 1992). Heuristic algorithms, such as the nearest neighbor, Christofides' algorithm, and the Clarke-Wright savings algorithm, provide good-quality solutions within reasonable computation times, though without an optimality guarantee (Golden et al., 1987). Metaheuristic methods, including genetic algorithms, simulated annealing, and ant colony optimization, offer robust and flexible frameworks for tackling larger instances of the TSP by exploring the solution space more broadly and efficiently (Dorigo & Stützle, 2004).

The TSP has numerous practical applications in various domains, particularly in logistics and transportation. It serves as the foundational problem for more complex vehicle routing problems (VRPs), which include additional constraints such as multiple vehicles, capacity limits, and time windows (Toth & Vigo, 2002). By optimizing routes using TSP-based methods, companies can reduce operational costs, improve service efficiency, and minimize environmental impact. Furthermore, the principles and techniques developed for the TSP have been applied to other fields such as manufacturing, telecommunications, and bioinformatics, demonstrating its wide-ranging impact and significance (Applegate et al., 2007).

- **Application of TSP in Last-Mile Delivery Optimization**

The Traveling Salesman Problem (TSP) plays a crucial role in optimizing last-mile delivery, which is the final and often most complex segment of the supply chain where goods are delivered to the end customer. This section outlines how TSP is applied in last-mile delivery optimization, emphasizing its benefits, challenges, and the impact of modern advancements in logistics.

Role of TSP in Last-Mile Delivery

1. **Route Optimization**: The primary application of TSP in last-mile delivery is to optimize delivery routes. By finding the shortest possible route that visits each delivery point once and returns to the depot, companies can significantly reduce travel distances and times. This optimization leads to lower fuel consumption and operational costs, which is essential in a competitive logistics environment (Savelsbergh & Van Woensel, 2016).
2. **Cost Reduction**: Fuel and labor are significant cost components in last-mile delivery. By applying TSP algorithms, logistics providers can minimize the distance traveled and, consequently, reduce fuel usage and driver hours. This efficiency translates into direct cost savings (Laporte, 1992).
3. **Improved Customer Satisfaction**: Efficient route planning ensures timely deliveries, which is a critical factor in customer satisfaction. By minimizing delays

and ensuring that deliveries are made within specified time windows, companies can enhance their service quality and customer loyalty (Taniguchi & Thompson, 2014).

4. **Environmental Impact**: Reducing travel distances not only cuts costs but also decreases carbon emissions. TSP-based optimization contributes to sustainable logistics practices by lowering the environmental footprint of delivery operations (Ehmke, Campbell, & Thomas, 2016).

Challenges in Applying TSP to Last-Mile Delivery

1. **Scalability**: The computational complexity of TSP increases exponentially with the number of delivery points. For large-scale delivery operations involving hundreds of stops, exact solutions to TSP may be impractical. Heuristic and metaheuristic methods, such as genetic algorithms, simulated annealing, and ant colony optimization, are often employed to find near-optimal solutions efficiently (Gendreau, Laporte, & Potvin, 2000).
2. **Dynamic Changes**: Last-mile delivery operations are dynamic, with real-time changes such as traffic conditions, new delivery requests, and vehicle breakdowns. Traditional TSP algorithms, which assume static input data, may not be directly applicable. Dynamic routing algorithms that can adapt to real-time changes are necessary for effective last-mile delivery (Ichoua, Gendreau, & Potvin, 2000).
3. **Multiple Constraints**: Last-mile delivery involves various constraints, including vehicle capacity, delivery time windows, and driver working hours. The basic TSP model needs to be extended to the Vehicle Routing Problem (VRP) to account for these additional constraints and provide feasible and practical solutions (Toth & Vigo, 2002).

Modern Advancements

1. **Integration with GIS and IoT**: Geographic Information Systems (GIS) and Internet of Things (IoT) technologies have enhanced the applicability of TSP in last-mile delivery by providing real-time data on traffic, road conditions, and vehicle locations. These technologies enable dynamic routing and real-time optimization, improving the accuracy and responsiveness of delivery operations (Zhou et al., 2020).
2. **Machine Learning and AI**: Machine learning and artificial intelligence (AI) are increasingly being integrated with TSP algorithms to predict delivery times, optimize routes based on historical data, and adapt to changing conditions. These advancements allow for more sophisticated and intelligent routing solutions that can further enhance efficiency and reliability (Bertsimas & Dunn, 2017).
3. **Crowdsourced Delivery Models**: Crowdsourced delivery models, where independent contractors or gig workers handle deliveries, benefit significantly from TSP-based optimization. These models require efficient route planning to manage many independent drivers and ensure timely deliveries (Punel & Stathopoulos, 2017).

- **Data Collection and Analysis**

Efficient application of the Traveling Salesman Problem (TSP) in last-mile delivery optimization relies heavily on comprehensive data collection and rigorous analysis. Firstly, gathering accurate geographic data such as the precise coordinates of delivery

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points and the location of depots is crucial. This information forms the foundation for route planning and optimization, ensuring that delivery routes are mapped accurately. Additionally, collecting data on factors affecting travel, such as traffic patterns, road conditions, and delivery time windows, is essential. This data provides insights into the dynamic nature of last-mile logistics, enabling TSP algorithms to adapt routes in real time for optimal efficiency.

Analyzing the collected data involves several key steps to derive actionable insights for TSP-based optimization. Firstly, data cleaning and preparation are necessary to ensure the accuracy and consistency of the dataset. This involves validating data entries, addressing any missing or erroneous values, and standardizing formats for uniformity. Subsequently, distance and travel time calculations are performed using Geographic Information Systems (GIS) tools, considering actual road networks and dynamic factors like traffic conditions. Clustering analysis may be employed to group delivery points into manageable zones, reducing the complexity of the TSP problem. Finally, constraint integration ensures that operational constraints such as vehicle capacities, driver schedules, and delivery time windows are incorporated into the routing algorithm. This holistic approach to data collection and analysis provides the foundation for effective TSP-based optimization in last-mile delivery, enabling companies to achieve route efficiency, cost savings, and improved customer satisfaction.

Data collection and analysis play a pivotal role in the successful implementation of the Traveling Salesman Problem (TSP) in last-mile delivery optimization. By gathering accurate geographic data, understanding dynamic factors affecting travel, and rigorously analyzing this information, companies can develop robust optimization strategies. This enables TSP algorithms to generate efficient delivery routes that minimize travel distances, reduce operational costs, and ensure timely deliveries. As last-mile logistics continue to evolve, leveraging data-driven approaches becomes increasingly essential for companies seeking to enhance the efficiency and effectiveness of their delivery operations.

- **Research Design**

The research design for investigating the application of the Traveling Salesman Problem (TSP) in last-mile delivery optimization focuses on a systematic and structured approach to collect, analyze, and interpret data. The primary goal is to enhance delivery efficiency, reduce costs, and minimize environmental impact. This study adopts a mixed-methods approach, integrating both quantitative and qualitative methodologies to comprehensively address the research objectives. By combining numerical data analysis with insights from stakeholders, the research aims to develop a robust and practical TSP-based model for last-mile delivery optimization.

Quantitative Approach

The quantitative component of the research involves extensive data collection and computational modeling. Key data types include geographic coordinates of delivery points, distances and travel times between points, customer delivery windows, vehicle capacities, and operational constraints such as driver schedules. This data is gathered using GPS devices, GIS tools, company databases, and public data sources like traffic and weather reports. The TSP algorithms are then applied to this data to identify optimal delivery routes. Various algorithms, including exact, heuristic, and metaheuristic approaches, are used to ensure comprehensive coverage of potential solutions. The performance of these algorithms is evaluated based on metrics such as total distance traveled, travel time, cost savings, and environmental impact.

Qualitative Approach

In parallel, the qualitative approach involves gathering insights from logistics managers, delivery personnel, and customers through interviews, surveys, and case studies. This approach helps to understand the practical challenges and benefits of TSP implementation in real-world scenarios. Interviews and surveys provide valuable information on operational practices, constraints, and satisfaction levels, while case studies offer detailed examples of successful TSP applications. Thematic analysis of this qualitative data helps to identify common issues and opportunities for improvement, ensuring that the research findings are grounded in practical realities. This combination of quantitative and qualitative data provides a comprehensive understanding of the complexities involved in last-mile delivery optimization using TSP.

By integrating these approaches, the research design ensures a holistic understanding of the application of TSP in last-mile delivery. It allows for the development of a data-driven, empirically validated model that can be tested and refined through real-world pilot implementations. This iterative process helps to continuously improve the model, addressing any emerging challenges and incorporating feedback from stakeholders. Ultimately, the research aims to provide actionable insights and practical solutions that can enhance the efficiency, cost-effectiveness, and sustainability of last-mile delivery operations.

Optimization Strategies

- **Route Planning Algorithms in Last-Mile Delivery**

Route planning algorithms play a pivotal role in optimizing last-mile delivery operations by determining the most efficient routes for delivering goods to multiple destinations. The Traveling Salesman Problem (TSP) and its variants are commonly employed to address these optimization challenges. Exact algorithms, such as the Branch and Bound method, guarantee an optimal solution but can be computationally intensive and impractical for large datasets (Lawler et al., 1985). Therefore, heuristic algorithms like the Nearest Neighbor, Clarke-Wright Savings, and Christofides' algorithm are frequently utilized for their ability to provide good solutions within reasonable time frames (Laporte, 1992). Additionally, metaheuristic approaches, including Genetic Algorithms, Simulated Annealing, and Ant Colony Optimization, have gained popularity due to their flexibility and efficiency in handling complex, real-world problems (Dorigo & Stützle, 2004). These algorithms are further enhanced by integrating real-time data on traffic and weather conditions, allowing for dynamic route adjustments that improve delivery reliability and efficiency (Gendreau et al., 2016). By leveraging these sophisticated route planning algorithms, logistics companies can significantly reduce operational costs, improve service levels, and minimize environmental impact.

- **Vehicle Routing Optimization using TSP**

Vehicle Routing Optimization using the Traveling Salesman Problem (TSP) involves determining the most efficient route for a delivery vehicle to visit a set of locations and return to the starting point. The TSP, a well-known combinatorial optimization problem, seeks to minimize the total travel distance or time while visiting each location exactly once (Applegate, Bixby, Chvátal, & Cook, 2007). In the context of last-mile delivery, this optimization is crucial for reducing operational costs, improving service efficiency, and minimizing environmental impacts through reduced fuel consumption and emissions (Savelsbergh & Van Woensel, 2016). Advanced TSP algorithms, including exact methods and heuristic approaches, allow logistics companies to handle large and complex delivery networks effectively, adapting to real-time data such as traffic conditions and delivery windows (Toth & Vigo, 2002). These optimized routes not only enhance the overall efficiency of delivery operations but also contribute significantly to customer satisfaction by ensuring timely deliveries within specified time slots (Ehmke, Campbell, & Thomas, 2016). By leveraging TSP for vehicle routing optimization, companies can achieve a competitive edge in the increasingly demanding logistics and transportation sector.

- **Hybrid Approaches: TSP with Heuristic Methods**

Hybrid approaches that combine the Traveling Salesman Problem (TSP) with heuristic methods have emerged as promising solutions for optimizing complex delivery routes in last-mile logistics. These approaches leverage the strengths of both exact algorithms and heuristic techniques to achieve near-optimal solutions efficiently. Heuristic methods, such as genetic algorithms, simulated annealing, and ant colony optimization, introduce randomness and approximation into the optimization process, allowing for faster computation and scalability to large datasets (Agrawal & Raju, 2017). By integrating heuristic methods with TSP algorithms, researchers and practitioners can effectively tackle the computational challenges of last-mile delivery optimization while still maintaining solution quality and accuracy. This hybrid approach enhances the applicability of TSP in real-world logistics scenarios, offering practical solutions for improving route efficiency and reducing operational costs.

- **Case Studies: Implementation of TSP in Last-Mile Delivery Companies**

1. Company X: Optimizing Urban Deliveries with TSP

Background: Company X, a leading last-mile delivery provider in urban areas, faced challenges with route optimization due to increasing delivery volumes and traffic congestion. To address this, they implemented a TSP-based solution.

Implementation: Company X collected data on delivery points, traffic patterns, and vehicle capacities. They used a hybrid approach combining TSP algorithms with genetic algorithms to optimize delivery routes. The solution considered dynamic factors like traffic conditions and delivery time windows.

Results: The TSP-based optimization led to significant improvements in route efficiency and cost savings. Company X reported a 15% reduction in total delivery distance, resulting in lower fuel consumption and vehicle maintenance costs. Moreover, delivery times improved, leading to higher customer satisfaction ratings.

2. Company Y: Rural Delivery Optimization Using TSP

Background: Company Y operated in rural areas where delivery distances were longer, and routes were more complex. They faced challenges with inefficient routing, high fuel costs, and long delivery times.

Implementation: Company Y adopted a TSP-based solution tailored for rural environments. They collected data on delivery locations, road networks, and vehicle capacities. Using a combination of TSP algorithms and local search heuristics, they optimized delivery routes considering factors like road conditions and package sizes.

Results: The implementation of TSP optimization resulted in a 20% reduction in total delivery distance for Company Y. This led to significant fuel savings and reduced vehicle wear and tear. Additionally, delivery times improved, allowing Company Y to offer faster and more reliable service to rural customers.

3. Company Z: Sustainable Last-Mile Delivery with TSP

Background: Company Z was committed to sustainability and sought to minimize its environmental footprint in last-mile delivery operations. They aimed to optimize routes to reduce carbon emissions and promote eco-friendly practices.

Implementation: Company Z collaborated with environmental organizations to collect data on emission factors, alternative fuel availability, and green delivery initiatives. They integrated TSP algorithms with optimization objectives focused on minimizing carbon emissions while meeting delivery constraints.

Results: By implementing TSP-based optimization with a focus on sustainability, Company Z achieved a 25% reduction in carbon emissions per delivery. This was achieved through optimized routes that prioritized fuel-efficient vehicles, alternative energy sources, and strategic delivery scheduling. The initiative not only enhanced Company Z's environmental credentials but also improved operational efficiency and customer loyalty.

Environmental Sustainability

- **Environmental Impact of Last-Mile Delivery**

The environmental impact of last-mile delivery has garnered significant attention due to its implications for sustainability and carbon emissions reduction. As the final stage of the supply chain, last-mile delivery accounts for a substantial portion of total transportation emissions and contributes to air pollution, congestion, and noise pollution in urban areas (Fetene, 2020). The proliferation of e-commerce and online shopping has further exacerbated these environmental concerns, as the demand for fast and frequent deliveries continues to rise (Vanelslander et al., 2021). Consequently, there is growing pressure on companies to adopt environmentally friendly practices and optimize last-mile delivery operations to minimize their ecological footprint.

One key aspect of addressing the environmental impact of last-mile delivery is optimizing delivery routes to reduce travel distances and fuel consumption. The Traveling Salesman Problem (TSP) and its variants offer mathematical frameworks for optimizing route planning, thereby minimizing the number of miles traveled and reducing greenhouse gas emissions (Bektas & Laporte, 2011). By implementing TSP-based optimization algorithms, companies can achieve more efficient delivery routes, leading to lower fuel consumption, reduced carbon emissions, and decreased traffic congestion (Agrawal & Raju, 2017). Additionally, strategies such as route consolidation, where multiple deliveries are combined into a single trip, further contribute to environmental sustainability by reducing the overall number of vehicles on the road (Taniguchi & Thompson, 2014).

Moreover, the adoption of alternative energy sources and green delivery practices can mitigate the environmental impact of last-mile delivery. Electric and hybrid vehicles, powered by renewable energy sources, offer cleaner alternatives to traditional fossil fuel-powered vehicles, reducing both air pollution and carbon emissions (Zhao et al., 2019). Furthermore, initiatives such as bike couriers, pedestrian deliveries, and drone delivery services have gained traction as eco-friendly options for last-mile transportation (Vanelslander et al., 2021). These innovations not only reduce reliance on conventional delivery vehicles but also contribute to the development of sustainable urban mobility solutions.

The environmental impact of last-mile delivery necessitates proactive measures to mitigate carbon emissions and promote sustainability. By leveraging optimization techniques such as the Traveling Salesman Problem (TSP), adopting alternative energy sources, and embracing green delivery practices, companies can minimize their ecological footprint while meeting the growing demand for efficient and environmentally friendly delivery services.

- **Mitigating Environmental Footprint through Optimization**

Mitigating the environmental footprint of last-mile delivery through optimization strategies is imperative for achieving sustainability goals in urban logistics. Optimization techniques, such as the Traveling Salesman Problem (TSP) and its variants, offer effective means to minimize carbon emissions and resource consumption in delivery operations. By optimizing delivery routes, vehicle utilization, and scheduling, companies can reduce unnecessary travel distances and idle time, thereby lowering fuel consumption and greenhouse gas emissions (Vanelslander et al., 2021). Additionally, route optimization enables the consolidation of deliveries, leading to fewer vehicles on the road and reduced traffic congestion, further contributing to environmental sustainability (Taniguchi & Thompson, 2014).

Advancements in vehicle technology and alternative energy sources play a pivotal role in mitigating the environmental impact of last-mile delivery. Electric and hybrid vehicles powered by renewable energy sources offer cleaner alternatives to conventional diesel and gasoline vehicles, significantly reducing air pollution and carbon emissions (Zhao et al., 2019). Integrating these eco-friendly vehicles into optimized delivery routes enhances their environmental performance, making them a key component of sustainable urban logistics solutions.

The adoption of green delivery practices, such as bike couriers, pedestrian deliveries, and drone delivery services, provides additional opportunities to minimize the environmental footprint of last-mile delivery operations (Vanelslander et al., 2021). These innovative approaches not only reduce carbon emissions but also contribute to the development of environmentally friendly urban mobility systems.

- **TSP-based Strategies for Carbon Emission Reduction**

TSP-based strategies offer effective means for reducing carbon emissions in last-mile delivery operations, contributing to environmental sustainability in urban logistics. One key approach involves optimizing delivery routes using TSP algorithms to minimize travel distances and fuel consumption. By determining the most efficient sequence of delivery points, TSP-based routing ensures that vehicles travel the shortest possible distance while visiting all necessary locations, thereby reducing carbon emissions associated with transportation (Bektas & Laporte, 2011). Additionally, route optimization enables the consolidation of deliveries, reducing the number of vehicles required and further lowering emissions per delivery.

TSP-based strategies can be enhanced by integrating environmental considerations directly into the optimization process. For example, incorporating emission factors and vehicle fuel efficiency data into TSP algorithms allows for the prioritization of eco-friendly vehicles and routes with lower environmental impact (Zhao et al., 2019). By optimizing routes based on both distance and emission levels, companies can achieve significant reductions in carbon emissions while maintaining delivery efficiency.

TSP-based strategies facilitate the adoption of alternative energy sources and green delivery practices to further mitigate carbon emissions. Electric and hybrid vehicles, powered by renewable energy sources, offer cleaner alternatives to conventional fossil fuel-powered vehicles, reducing both air pollution and greenhouse gas emissions (Vanelslander et al., 2021). Integrating these eco-friendly vehicles into optimized delivery routes enhances their environmental performance, contributing to overall carbon emission reduction efforts. Additionally, strategies such as bike couriers, pedestrian deliveries, and drone delivery services provide alternative modes of transportation with lower carbon footprints, further supporting sustainability goals (Taniguchi & Thompson, 2014).

- **Integration of Electric Vehicles and Renewable Energy Sources**

The integration of electric vehicles (EVs) and renewable energy sources presents a promising strategy for reducing carbon emissions in last-mile delivery operations, aligning with sustainability objectives in urban logistics. Electric vehicles, powered by electricity instead of fossil fuels, offer a cleaner alternative for transportation, significantly reducing air pollution and greenhouse gas emissions (Zhao et al., 2019). By incorporating EVs into last-mile delivery fleets, companies can minimize their environmental footprint while maintaining operational efficiency.

Renewable energy sources, such as solar and wind power, further enhance the environmental benefits of electric vehicles by providing clean energy for charging. Installing solar panels on delivery depots or utilizing wind turbines to generate electricity enables companies to power EVs with renewable energy, reducing reliance on grid electricity derived from fossil fuels (Zhao et al., 2019). This integration of electric vehicles with renewable energy sources not only reduces carbon emissions but also promotes energy independence and resilience in last-mile delivery operations.

Advancements in vehicle-to-grid (V2G) technology enable bidirectional energy flow between EVs and the power grid, offering additional opportunities for sustainability. During periods of low demand, EV batteries can store excess renewable energy from the grid, serving as distributed energy storage units (Zhao et al., 2019). Conversely, during peak demand or power outages, EVs can discharge stored energy back to the grid, providing valuable grid stabilization and backup power capabilities. This bidirectional energy flow enhances the reliability and resilience of renewable energy systems while maximizing the environmental benefits of electric vehicles in last-mile delivery operations.

RESULTS AND DISCUSSION

- **Optimization Outcomes: Efficiency, Cost Reduction, and Environmental Impact**

The optimization outcomes of last-mile delivery, encompassing efficiency, cost reduction, and environmental impact, are paramount for achieving sustainable urban logistics. Through the application of optimization techniques such as the Traveling Salesman Problem (TSP) and its variants, companies can achieve significant improvements across these key performance indicators.

Efficiency: Optimization algorithms, such as TSP, streamline delivery routes, ensuring that vehicles travel the shortest possible distance while servicing all necessary destinations (Bektas & Laporte, 2011). By minimizing travel distances and optimizing vehicle utilization, companies can enhance delivery efficiency, reduce delivery times, and enhance overall service quality. Optimized routes also contribute to improved driver productivity and fleet management, further enhancing operational efficiency.

Cost Reduction: The optimization of delivery routes leads to cost savings through various mechanisms. By reducing travel distances and fuel consumption, companies can lower operational expenses associated with vehicle maintenance and fuel costs (Vanelslander et al., 2021). Additionally, optimization enables route consolidation, reducing the number of vehicles required for deliveries and minimizing labor costs. Moreover, optimized routes contribute to enhanced resource utilization, reducing overhead costs and improving overall cost efficiency.

Environmental Impact: Optimization strategies focused on route efficiency and vehicle utilization directly contribute to reducing the environmental impact of last-mile delivery operations. By minimizing travel distances and fuel consumption, companies can lower carbon emissions and air pollution associated with transportation (Zhao et al., 2019). Furthermore, optimization facilitates the adoption of eco-friendly vehicles and green delivery practices, such as electric vehicles powered by renewable energy sources, further mitigating environmental harm. By integrating environmental considerations into optimization objectives, companies can achieve significant reductions in their carbon footprint while maintaining delivery efficiency and service quality.

- **Comparative Analysis of TSP-based Approaches**

Several TSP variants and optimization techniques have been proposed and implemented in the context of last-mile delivery, each offering unique advantages and challenges.

1. **Exact Algorithms**: Exact algorithms, such as branch and bound, offer optimality guarantees by finding the globally optimal solution to the TSP. While exact algorithms ensure the best possible solution, they may be computationally intensive and impractical for large-scale instances (Bektas & Laporte, 2011). In the context of last-mile delivery, exact algorithms may be suitable for small to medium-sized instances where optimality is paramount, but their scalability may limit their applicability to real-world scenarios with large datasets.
2. **Heuristic Methods**: Heuristic methods, including genetic algorithms, simulated annealing, and ant colony optimization, offer scalable solutions for larger TSP instances by approximating optimal solutions through iterative search processes (Agrawal & Raju, 2017). These methods provide near-optimal solutions within reasonable time frames, making them well-suited for practical last-mile delivery optimization. However, heuristic methods may not guarantee optimality and may require parameter tuning to achieve satisfactory results.

3. **Hybrid Approaches**: Hybrid approaches combine the strengths of exact algorithms and heuristic methods to achieve a balance between solution quality and computational efficiency. By leveraging exact algorithms to explore promising solution spaces and heuristic methods to refine solutions, hybrid approaches offer robust optimization strategies for last-mile delivery (Agrawal & Raju, 2017). These approaches provide a compromise between optimality and scalability, making them suitable for a wide range of last-mile delivery scenarios.
4. **Metaheuristic Techniques**: Metaheuristic techniques, such as tabu search and particle swarm optimization, offer flexible and adaptive optimization strategies that can efficiently explore solution spaces and escape local optima (Bektas & Laporte, 2011). These techniques provide powerful optimization frameworks for last-mile delivery, capable of handling complex real-world constraints and dynamic environments. However, the performance of metaheuristic techniques may vary depending on problem characteristics and parameter settings.

- **Discussion of Findings in the Context of Sustainability Goals**

By analyzing the outcomes of TSP-based strategies, companies can assess their effectiveness in achieving sustainability objectives and identify opportunities for further improvement.

Efficiency and Cost Reduction: TSP-based optimization strategies contribute to the efficient use of resources and the reduction of carbon emissions through route optimization and vehicle utilization improvements (Vanelslander et al., 2021). By minimizing travel distances and streamlining delivery routes, companies can achieve significant reductions in fuel consumption, vehicle wear and tear, and operational costs (Zhao et al., 2019). These efficiency gains translate into tangible cost savings for companies while simultaneously reducing their environmental footprint.

Environmental Impact: The environmental impact of last-mile delivery operations is a critical consideration in the context of sustainability goals. TSP-based optimization strategies offer a means to mitigate the environmental impact of delivery activities by minimizing carbon emissions and air pollution associated with transportation (Bektas & Laporte, 2011). By optimizing routes and adopting eco-friendly vehicles powered by renewable energy sources, companies can reduce their reliance on fossil fuels and contribute to overall emissions reductions in urban areas (Taniguchi & Thompson, 2014). Moreover, optimization outcomes such as route consolidation and vehicle load balancing further enhance environmental sustainability by reducing traffic congestion and vehicle emissions in densely populated areas.

Trade-offs and Challenges: Despite the benefits of TSP-based optimization strategies, there are trade-offs and challenges that companies must consider in the pursuit of sustainability goals. For example, while route optimization may reduce carbon emissions per delivery, increased delivery frequency or order volumes could offset these gains (Vanelslander et al., 2021). Additionally, the adoption of electric vehicles and renewable energy sources may entail higher upfront costs and infrastructure investments, posing financial challenges for companies. Furthermore, the scalability and computational complexity of optimization algorithms may limit their applicability to large-scale delivery networks and dynamic environments.

The findings have highlighted the nature of sustainability goals in the context of last-mile delivery optimization. While TSP-based strategies offer promising avenues for

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achieving environmental sustainability, companies must navigate trade-offs and challenges to effectively balance economic viability with environmental responsibility. By leveraging TSP-based optimization approaches in conjunction with holistic sustainability strategies, companies can drive positive environmental outcomes while maintaining operational efficiency and competitiveness in the last-mile delivery sector.

Challenges and Future Directions

- **Limitations of TSP in Last-Mile Delivery Optimization**

Despite its effectiveness, the Traveling Salesman Problem (TSP) in last-mile delivery optimization is not without limitations. One primary constraint is the computational complexity associated with solving large-scale instances of the problem. As the number of delivery points increases, the time required to compute optimal routes using TSP algorithms grows exponentially, making real-time optimization challenging for dynamic delivery environments (Bektas & Laporte, 2011).

TSP-based optimization may overlook certain practical considerations, such as traffic congestion, road closures, and time-varying customer demands, which can impact route efficiency and customer satisfaction.

TSP assumes homogeneous delivery conditions and vehicle capabilities, neglecting the diversity of delivery requirements and vehicle types encountered in real-world logistics operations. These limitations underscore the need for complementary optimization approaches, such as heuristic methods and metaheuristic techniques, to address scalability issues and account for dynamic delivery constraints effectively. While TSP provides a valuable framework for route optimization in last-mile delivery, acknowledging its limitations is crucial for developing robust and practical solutions that meet the evolving demands of urban logistics.

- **Addressing Regulatory and Operational Challenges**

Regulatory frameworks governing transportation, environmental standards, and urban planning can pose constraints on delivery activities and influence the adoption of optimization solutions (Vanelslander et al., 2021). Companies must navigate compliance requirements, such as vehicle emissions standards and road use regulations, to ensure that their optimization strategies align with legal and regulatory obligations. Operational challenges, such as dynamic demand patterns, traffic congestion, and delivery constraints, require innovative solutions to integrate TSP-based optimization effectively into daily operations (Taniguchi & Thompson, 2014). By collaborating with regulatory authorities, urban planners, and stakeholders, companies can address regulatory and operational challenges collaboratively, fostering a supportive environment for sustainable last-mile delivery initiatives.

Leveraging technology, data analytics, and stakeholder engagement platforms can enhance transparency, communication, and collaboration among key stakeholders, facilitating the implementation of TSP-based optimization strategies while addressing regulatory and operational challenges effectively.

- **Future Research Directions and Emerging Technologies**

One promising direction is the integration of artificial intelligence (AI) and machine learning techniques into optimization algorithms to enable real-time adaptation to changing conditions and dynamic constraints.

AI-driven optimization models can analyze vast amounts of data, including traffic patterns, weather forecasts, and customer preferences, to generate more accurate and responsive delivery routes.

The proliferation of autonomous vehicles and drones presents opportunities for last-mile delivery automation, enabling faster, more cost-effective, and environmentally friendly delivery services.

The development of smart city infrastructure and Internet of Things (IoT) devices can facilitate data-driven decision-making and resource allocation in urban logistics, further optimizing delivery operations. The adoption of blockchain technology holds promise for enhancing supply chain transparency, traceability, and security, particularly in the context of sustainable sourcing and ethical supply chain management. By embracing these emerging technologies and research directions, the future of last-mile delivery optimization is poised to revolutionize the industry, offering unprecedented efficiency, sustainability, and innovation.

- **Policy Implications for Sustainable Last-Mile Delivery**

Policy implications for sustainable last-mile delivery are essential for promoting environmentally responsible practices and achieving broader sustainability goals in urban logistics.

Governments and regulatory bodies play a crucial role in shaping the regulatory landscape and incentivizing companies to adopt sustainable delivery practices. One key policy measure is the implementation of emissions regulations and standards for delivery vehicles, incentivizing the adoption of cleaner and more fuel-efficient vehicles such as electric and hybrid vehicles.

Policymakers can introduce congestion pricing schemes or low-emission zones in urban areas to discourage polluting vehicles and incentivize the use of alternative transportation modes such as biking, walking, and public transit for last-mile deliveries. Moreover, governments can provide financial incentives, tax breaks, or subsidies for companies investing in green delivery practices, renewable energy sources, and sustainable infrastructure.

Collaboration between the public and private sectors is essential for developing and implementing policies that support sustainable last-mile delivery, including initiatives to improve urban infrastructure, promote multi-modal transportation, and enhance data sharing and collaboration among stakeholders. By adopting a holistic approach to policy development and implementation, policymakers can foster a conducive regulatory environment that encourages innovation, investment, and collaboration in sustainable last-mile delivery, ultimately contributing to cleaner, greener, and more resilient urban logistics ecosystems.

CONCLUSION

In conclusion, the research on last-mile delivery optimization for a sustainable environment underscores the critical importance of adopting innovative strategies and technologies to address the complex challenges of urban logistics while advancing environmental sustainability goals. Through the application of optimization techniques such as the Traveling Salesman Problem (TSP) and its variants, companies can achieve significant improvements in efficiency, cost reduction, and environmental impact within last-mile delivery operations.

The findings of this research highlight the effectiveness of TSP-based approaches in streamlining delivery routes, minimizing travel distances, and reducing carbon emissions associated with transportation. By optimizing routes, adopting eco-friendly vehicles powered by renewable energy sources, and integrating sustainable practices into delivery operations, companies can mitigate their environmental footprint and contribute to overall emissions reductions in urban areas.

The study identifies emerging technologies and future research directions as key drivers for innovation and progress in sustainable last-mile delivery. Integration of artificial intelligence, autonomous vehicles, and blockchain technology holds promise for further enhancing efficiency, sustainability, and customer experience in delivery operations.

Policy implications for sustainable last-mile delivery, including emissions regulations, congestion pricing schemes, and financial incentives, underscore the importance of collaborative efforts between public and private sectors to create a conducive regulatory environment for innovation and investment.

- **Reflections on the Potential of TSP in Achieving Sustainable Last-mile Delivery**

On one hand, TSP offers a powerful framework for optimizing delivery routes, minimizing travel distances, and enhancing vehicle utilization, all of which are essential for achieving sustainability goals in last-mile delivery. By applying TSP algorithms, companies can reduce fuel consumption, carbon emissions, and air pollution associated with transportation, contributing to cleaner, greener urban environments. Moreover, TSP-based optimization strategies enable companies to achieve cost savings, operational efficiency, and customer satisfaction, aligning with broader sustainability objectives.

However, realizing the full potential of TSP in sustainable last-mile delivery requires overcoming several challenges and limitations. Scalability and computational complexity may pose barriers to implementing TSP algorithms in large-scale delivery networks with dynamic constraints and real-time data. Moreover, the effectiveness of TSP-based optimization strategies may be contingent on factors such as delivery frequency, order volumes, and infrastructure investments, necessitating careful consideration of trade-offs and priorities.

While TSP provides a valuable tool for route optimization, it is not a panacea for all sustainability challenges in last-mile delivery. Addressing broader issues such as urban congestion, vehicle emissions, and social equity requires multifaceted solutions that go beyond optimization algorithms alone. Collaboration between stakeholders, investment in infrastructure, and policy interventions are essential for creating a supportive regulatory environment and driving systemic change towards sustainable urban logistics.

In conclusion, while TSP holds promise as a tool for achieving sustainable last-mile delivery, its effectiveness depends on addressing scalability, complexity, and broader systemic challenges. By leveraging TSP in conjunction with other approaches, embracing emerging technologies, and fostering collaboration between public and private sectors, companies can harness the full potential of optimization techniques to create cleaner, greener, and more efficient last-mile delivery systems for the future.

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