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Last-Mile Delivery Optimization: Recent Approaches and Advances

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Abstract

There are numerous challenges in the last mile of urban logistics operations related to efficiency, resource allocation, environmental sustainability, and delivery operations. Technological innovation in recent years is trying to fill these loopholes and bring out efficient, reliable, and sustainable last-mile delivery. This paper provides a summary of the current optimization approaches in last-mile delivery, covering traditional Linear Programming methods, sophisticated algorithmic techniques known as metaheuristic methods, Artificial Intelligence (AI) based approaches, experience-based methodologies, and energy conservation techniques. These sets of optimization techniques—derived from optimization theory and computational algorithms—are diverse in their strategies for route planning, resource allocation, and energy management and tailored to the complex nature of urban delivery networks. In this regard, promising future technologies have also been discussed to re-orient last-mile delivery. Autonomous delivery by drones is one such game-changing solution that can enable rapid and eco-friendly delivery capabilities. Smart delivery acceptance systems through extensive use of advanced sensor technologies and data analytics help simplify parcel reception processes and make them much more efficient and safer. In the context of changing customer preferences and the emergence of e-commerce, the optimization of the last mile is critical in satisfying increasing demand while ensuring environmental sustainability and operational efficiency. Such innovative technologies and optimization strategies will enable delivery providers to better manage urban logistics challenges to deliver better customer experience and achieve sustainable growth in the last mile of delivery.

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1. Introduction

The last-mile in the contemporary logistics business of commerce is more critical than ever. Last-mile means the final stretch of a product from the distribution center to a customer's doorstep, which is always a test of efficiency, reliability, and sustainability for urban logistics. Last-mile delivery trends show that people are finding this mode of commerce increasingly in demand. E-commerce continues to become popular and online shopping becomes a new trend that is demanding efficient last-mile delivery. The convenience of fast delivery services is often one of the priority choices for consumers whose busy schedule requires that everything be done quickly. Companies invest a great deal in last-mile delivery technologies and strategies to capture this demand (Biancolin and Rotaris, 2024; Karavaeva, 2023). The deployment of self-driven delivery drones, smart delivery acceptance systems, and other emerging technologies introduces a future where last-mile delivery plays a leading role in urban logistics (Gundu, 2020). As technology changes the study of Urban Logistics, it then becomes a leading consideration toward making companies successful in this Digital Economy. The delivery providers will find out a better and more efficient way to go around the challenges of urban logistics: serving customers better with less environmental impact and reduced operational load.

The nature of last-mile delivery is complex. Urban congestion, dynamic customer demand, and the necessity of keeping green footprints put several factors into play that make last-mile delivery difficult to manage. Traditional last-mile delivery methods, relying on manual route planning and resource allocation, are unable to meet the ever-growing modern requirements of the urban consumer, resulting in inefficient routes, increased pollution, and lost consumer satisfaction (Silva et al., 2023). Manual planning often led to suboptimal routes, contributing to congestion and environmental degradation. As consumer expectations for faster, more convenient delivery options grew, the shortcomings of these outdated methods became increasingly apparent, prompting a shift towards innovative solutions. As opposed to this, the logistics industry has reverted to advanced technology innovation and sophisticated optimization techniques to make the logistics of last-mile delivery operations streamlined and more efficient (Boysen et al., 2021).

This paper will discuss recent advancements in last-mile delivery optimization techniques and survey the broad spectrum of approaches (See Figure 1) that utilize state-of-the-art technology and computational algorithms. From classical Linear Programming methods to sophisticated algorithmic strategies and AI driven solutions, a range of optimization methodologies has emerged to confront the challenges of urban delivery networks. Among these, AI-based methods identify the data and use optimization algorithms to undertake dynamically adaptive and innovative route planning, based on real-time conditions and the customers' preferences. Linear programming techniques present a mathematical framework for optimal resource allocation and route planning, minimizing the costs and maximizing delivery efficiency. Metaheuristics are heuristic approaches for finding approximate solutions to optimization problems, performing search in a complex search space for near-optimal solutions. Energy conservation strategies look at minimizing energy consumption in delivery operations by exploring new, innovative technologies, and sustainable practices. Experience-based methods interpret past delivery experiences and driver expertise for making decisions and for improving overall performance. In all this variety of approaches, they collectively work towards the advancement of last-mile delivery optimization, resolving problems and opening new roads for innovation in urban logistics networks.

The paper will look into the future technologies that are expected to change last-mile delivery and include promising potential. Self-driven delivery drones equipped with high-level navigation systems and payload capacities give the vision of rapid, environmentally friendly delivery solutions. Smart delivery acceptance systems that use sensors and data analysis makes the parcel reception process faster and more efficient. It also improves the security in urban delivery networks. In the nutshell, this paper aims to bring insights into the current and future of last-mile delivery and what that means for the logistics industry.

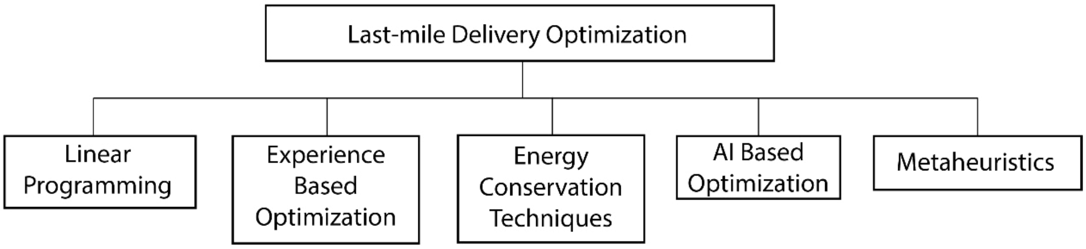

Figure 1: Optimization methodologies in last-mile-delivery.

2. Prevailing optimization methods in last-mile delivery

Last-mile delivery is sponsored by several optimization methods to make it efficient, cost-effective, and environmentally friendly. These methods are practical in dealing with a network of logistics in cities characterized by congestion, dynamic demand patterns, and sustainability challenges. It is paramount to understand and discuss these prevailing optimization methods, as they represent novel solutions to the pressing issues faced by delivery networks today. With deep analysis into each method, one may see its strengths and weaknesses and find out applications potential to lead the way to more effective and sustainable last-mile delivery solutions. Table 1 provides a summary of the literature reviewed in this section. t

2.1. Linear programming

The linear programming methodology provide a mathematical framework for optimal resource allocation and route planning targeted at cost minimization with simultaneous delivery efficiency maximization. Systematic analysis of factors such as vehicle capacity, delivery locations, and the time constraint can value delivery operations with the help of linear programming techniques. Understanding the principles and applications of linear programming in last-mile delivery is central to unlocking its potential to solve logistical challenges of today's urban consumers.

There have been a series of studies that have considered optimization problems in the last-mile. Each of these studies applied different methods adapted to the problem's nuances. (Nguyen et al., 2022) formed the Parallel Drone Scheduling Traveling Salesman Problem using Mixed Integer Linear Programming. It solves it using a Ruin and Recreate Algorithm. Their work tested 90 instances and resulted in brand-new best solutions in 26 instances. The objective function (Nguyen et al., 2022) considered, shown below, minimizes transportation cost.

$$C\sum_{\mathrm{i}}\sum_{\mathrm{j}}\mathrm{d_{ij}x_{ij}} + C'\sum_{\mathrm{i}}\sum_{k}\mathrm{d}'_k\mathrm{y_i}$$

Where C and C' are the costs of transporting a drone and a truck for a certain distance. $\mathrm{d_{ij}}$ is the distance a drone covers between i and j. d'_k is the total flying distance in serving a customer k. $\mathrm{x_{ij}}$ and $\mathrm{y_i}$ are binary variables indicating the participation of $\mathrm{d_{ij}}$ and d'_i in the cost function. The constraints considered by (Nguyen et al., 2022) are not shown for brevity. The strength lies in the ability to handle complex delivery scenarios, contributing to improved efficiency in last-mile operations. The algorithm finds 26 new best solutions out of the 90 considered instances. However, while cutting transportation costs are vital for the logistics company, customer centric constraints such as timely delivery was not considered in the paper.

In another attempt involving drones and road delivery vehicles (trucks), (Murray and Raj, 2020) first described the delivery problem as a Mixed Integer Linear Program. The study assumes last-mile delivery consists of the steps in

Figure 2. The insights from this study give an idea of the optimal thresholds of deployment of UAVs (Unmanned Aerial Vehicles) which offers a glimpse into the practical challenges in the implementation of optimization algorithms in real-world delivery systems. The main objective of (Murray and Raj, 2020) is to minimize the time required to deliver orders to customers and returning to the depot, as such, the cost function shown below was constrained by the arrival time, service time, and completion time of the trucks and UAVs involved in the delivery. It was shown that when there were 100 customers 56.98% of trucks had same location conflicts which had to be resolved by other means.

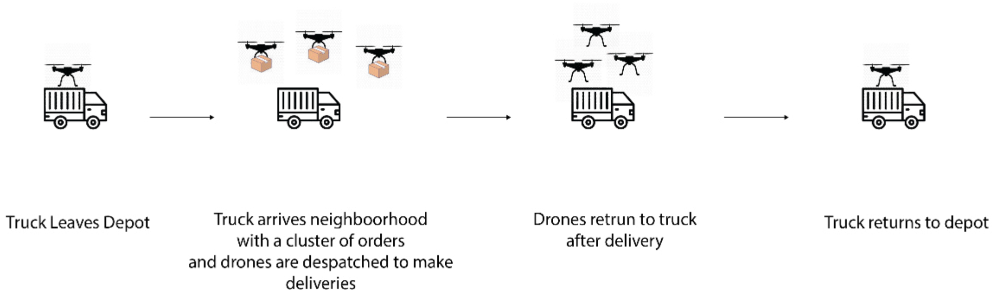

Figure 2: Steps involved in last mile delivery logistics.

2.2. Metaheuristics

To date, different challenges have been addressed by researchers with various optimization methodologies based on metaheuristics applied in last-mile delivery. Genetic Algorithms are one of the optimization techniques that are strongly set to imitate natural evolution in solving applied complex problems.

A Genetic Algorithm (GA) starts off with a population of candidate solutions, encoding each as a chromosome, usually randomly. At each successive generation or iteration, the fitness value of each subject is evaluated based on a pre-defined fitness function. The selection process then chooses the fittest individuals to become parents for the next generation. These parents then undergo crossover whereby the genetic material of these two parents is combined to generate offspring, hence introducing new variations in the genotypes. Some of the off-springs undergo mutation, wherein some genes of the off-spring are randomly changed, thereby keeping the diversity of the population in check. This process of selection, crossover, and mutation is repeated iteratively over many generations, whereby the population, over time, evolves to better solutions. The process terminates on satisfaction of a certain stopping criterion, returning the best solution found so far, which could be based on a maximum number of generations or a satisfactory fitness level. The steps in genetic algorithm is summarized in Figure 3. Genetic Algorithms could provide high functionality in last-mile delivery optimization by efficiently looking through complex and dynamic search spaces. A GA encodes the delivery routes of a drone into chromosomes for the evaluation of each route according to chosen criteria, such as delivery time, energy consumption, or operational costs. For example, GA can be used to pick out the best routes in terms of delivery route optimization, cross efficient segments from other routes, add a little mutation that searches for newer paths, and repeat the same to come up with a more efficient delivery network. An application of this might be the optimization of a drone fleet to achieve minimum total delivery time, subject to battery constraints, in pursuit of having a robust and efficient delivery system that could adapt to changes in demand and environmental conditions in real time.

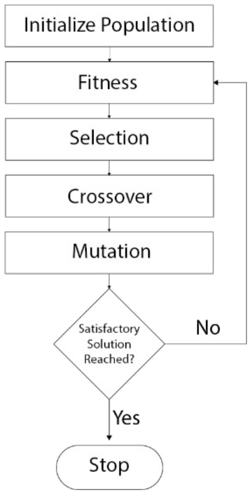

Figure 3: Genetic algorithm

(Rinaldi et al., 2023) conducts the Travelling Salesman Problem within last-mile delivery scenarios; they proposed two hybrid genetic algorithms in an attempt to minimize total delay. This result has shown that their hybrid genetic algorithms beat normal techniques in speed and accuracy of optimizing delivery assignments. Their flexibility and robustness contribute to make them ideal for optimizing delivery routes.

2.3. Experience based optimization

Experienced-based approaches refer to the use of past delivery data and expertise from experienced drivers to inform the decision-making process. Such methods provide insights in route planning, resource allocation, and delivery operations, capitalizing on knowledge drawn from real-world experiences. Experienced-based optimization strategies address ways of improving efficiency, reliability, and customer satisfaction in urban logistics networks.

(Mo et al., 2023) explains how experienced drivers outperforms algorithms while in route planning hold many efficiencies. They explain how the use of historical data for using neural network models helps in the better accuracy of the work. It enhances the accuracy of the route planning and, therefore, the improved delivery time and customer satisfaction.

2.4. Energy conservation techniques

In last-mile delivery, the mission of saving energy would be of paramount importance given the significant environmental and economic implications of energy consumption. Congestion, emissions, and depletion of resources call for a concerted effort to optimize energy use in delivery operations. Energy conservation strategies represent an effective approach toward sustainable performance and increased efficiency and cost reduction. By adopting innovative technologies and sustainable practices, energy conservation techniques in last-mile delivery will minimize their energy consumption, effectively reducing their environmental impact and promoting economic viability. This section reviews the energy conservation techniques within last-mile delivery, applied to their applications, benefits, and potential role in making an urban logistics system sustainable and resilient.

(Pan et al., 2021) provide a method through which a UAV on its last-mile delivery assignment can save energy while in transit by charging some. A UAV to collect items for delivery will take off from a warehouse, find some crowdsourced bus that will take it toward the destination, and get recharged while on the bus. Upon reaching the destination, the UAV is launched from the bus for delivering the package. The same methodology is followed in the return mission of the UAV from the warehouse. It helps to improve energy efficiency of the UAV-based delivery system by minimizing the chances of a direct flight and generating recharging opportunities.

2.5. Optimizations based on artificial intelligence

Given the catholic change in almost every sector, including last-mile delivery operations, AI is set to revolutionize the efficiency, reliability, and sustainability in urban logistics networks. This essentially levers on advanced machine learning algorithms, data analytics, and optimization techniques to avail unparalleled opportunities for AI-based approaches. These methodologies exploit the huge data resources to derive insights, forecast demand trends, and dynamically optimize the delivery routes in real time. With the continuous consumer expectation for fast, user-friendly, and eco-conscious delivery services, AI-based optimization strategies become essential tools to satisfy these evolving demands while simultaneously making downs in operational costs and ecological footprints. In this literature review, we embark on an exploration of AI-based optimization strategies in the context of last-mile delivery, focusing on their practical applications, inherent advantages, and profound impacts on reshaping the trajectory of urban logistics.

In pursuit of last-mile delivery effectiveness, many machine learning algorithms have been employed to solve specific problems. (Luo et al., 2023) presents a lightweight deep neural network model and also exploits these competencies for accurate position prediction of a parcel for delivery despite the interference of poor GPS signals or disruptions. This application would entail the versatility of AI in solving logistical challenges for effectual delivery plans.

Table 1: Literature Review Summary

Reference	Relevance	Optimization Type	Obtained Result
(Nguyen et al., 2022)	Introduced drone travel cost minimization technique.	Linear Programming	Found 26 new solutions out of 90 well known instances.
(Murray and Raj, 2020)	Highlights the impact of UAV deployment on delivery time, emphasizing the importance of finding an optimal balance to avoid diminishing returns.	Linear Programming	Only 56.98% location conflicts when there are 100 customers.
(Rinaldi et al., 2023)	Provides insights into optimization techniques	Metaheuristics	Lower optimality (~3%) but faster computational time
(Mo et al., 2023)	Human knowledge inspired approach.	Experience Based, AI	36% increase in prediction accuracy and reduces the disparity between actual and predicted routes by 15%
(Pan et al., 2021)	Understanding energy conservation and replenishing methods in UAVs.	Energy Conservation	Improved drone energy saving
(Luo et al., 2023)	Applying computer vision to last mile delivery	Artificial Intelligence	Model Mean average precision of 99.37% in detecting obstacles.

3. The future of optimization in last-mile delivery

What does the future of optimization in last-mile delivery look like? This includes advances in autonomous delivery drones, which might one day offer rapid and inexpensive, eco-friendly, and maintenance-free delivery solutions with highly advanced levels of navigation systems and payload capacities. Other important developments include smart delivery acceptance systems equipped with sensors and data analytics for receiving packages and making the entire process more efficient and secure within urban delivery networks. Finally, blockchain technology provides an opportunity for transparent and secure delivery tracking and verification systems that help build trust and reliability within the delivery process. Augmented reality is another technology that has the potential to make logistics operations more efficient by providing real-time information on deliveries and navigation guidance throughout the entire route planning and handling of the package. These technologies are continuously designed to shape the last-mile delivery landscape in terms of efficiency, reliability, and sustainability in urban logistics networks.

3.1. Autonomous drones and robots

Some of the recent advances adopted in literature point to a very promising direction of autonomous last-mile delivery operations drones. The application of autonomous drones for medical assistance is first brought up, underlining their potential to carry time-critical items such as medical supplies, vaccines, and emergency equipment. Application of Reinforcement Learning algorithms, as proposed by (Jacob et al., 2022), creates a framework for autonomous drone navigation focusing on safety and efficiency. It satisfies more than the growing need for effective delivery platforms across different industries and works to lay a foundation in optimizing drone navigation within the domain of urban scenarios.

3.2. Smart delivery acceptance system

This includes the incorporation of intelligent delivery acceptance mechanisms, specifically smart locker systems, in rural and urban regions that are difficult to handle logistically. According to (Gundu, 2020), such systems can help bridge the digital divide by offering automated, secure, and convenient parcel collection points within a community by leveraging from existing access methods as laid down by the Unified Theory of Acceptance and Use of Technology. In this way, the Enhanced Unified Theory of Acceptance and Use of Technology (EUTAUT) proposed in this study can provide a foundation for inclusive solutions.

3.3. Blockchain

Blockchain technology has influenced the evolution of last-mile delivery in the light of prevalent, traditional problems. For example, (Silva et al., 2023) present a new SCM framework using a consortium blockchain, which allows for a resilient last-mile delivery in the presence of the recent surge in crowdsourced vehicles and UAVs. This constitutes an end-to-end framework that will smartly integrate vehicles and UAVs while ensuring transparency and timelessness in delivery operations. It therefore preeminently Who delegate-accounts for delivery tasks through blockchain mechanisms hosted by smart contracts, considering speed and cost factors. It therefore gives more expanded scope to process visibility and accountability. The paper presents experimental results of the framework that validate its effectiveness by citing percentage increases in task allocation, reward, and delivery time over existing benchmarks. All these together prove the utilization of a blockchain for optimizing last-mile delivery operations.

4. Conclusion

Optimizing last-mile delivery incorporates various methodologies and technologies that aid in valorizing the increasing demand of modern commerce. It has been a fast progression of development, from autonomous drones to smart lockers, blockchain-based frameworks, and so on. Autonomous vehicles, from drones to ground-based robots, hold immense potential for empowering last-mile logistics—especially in the urban setting of highly populated areas—to deliver goods quickly and flexibly. Artificial intelligence and machine learning algorithms also empower predictive analytics, route optimization, and real-time demand forecasting for a better layout of delivery routes and schedules. Furthermore, it allows emerging blockchain-based technologies to provide higher levels of transparency, trust, and security in last-mile transactions, which will lead toward a decentralized democratized delivery network. Expert Opinion: The future related to the last mile in delivery is promising and has practical use cases that will deliver efficiency, reliability, and sustainability, bringing forth a new age of convenience and accessibility to consumers worldwide.

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