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Optimising Drone-Assisted Logistics for Urban Last-Mile Delivery: An Overview of Applications, Methodologies, and Emerging Trends

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Abstract: The rapid evolution of drone-assisted logistics for urban last-mile (ULM) delivery has garnered significant interest from both academia and industry. This article presents a comprehensive review of the state-of-the-art research and practical implementations of ULM systems, focusing on the use of unmanned aerial vehicles (UAVs) for the final stage of goods and parcel delivery in urban environments. The applicability of UAV-based logistics across various contexts, including urban and rural areas, is examined, with real-world case studies highlighted to demonstrate practical uses. Key methodologies and models employed in optimising UAV routing and operations are discussed, particularly those that enhance the efficiency and reliability of ULM. The critical advantages and limitations of drone-assisted last-mile logistics are analysed, providing insights into the operational, regulatory, and technological challenges. The discussion is further expanded by addressing emerging trends in UAV technology, as well as innovations in drone deployment strategies and the evolving regulatory landscape. In conclusion, potential theoretical advancements and future applications of ULM systems are outlined, with an emphasis on integrating drones into broader logistics networks and smart city frameworks. The insights offered aim to guide future research and practical developments in this rapidly advancing field.

Keywords: Urban last-mile (ULM) delivery; Drone routing optimisation; Unmanned aerial vehicles (UAVs); Logistics operations; Drone-assisted delivery; Smart city logistics

1 Introduction

Urban Last Mile, or ULM, delivery regards all logistics activities linked to delivering goods to private customer households in urban areas (Figure 1). There are two global trends, urbanization and e-commerce, influencing the request for last-mile delivery services [1]. However, despite significant advancements in logistics, a gap remains in addressing the increasing demand for cost-effective and sustainable last-mile delivery solutions, particularly through the integration of UAVs or drones. This paper addresses this research gap by exploring the potential of drone-assisted last-mile delivery logistics, identifying key challenges, and proposing strategies to overcome them. Given the rapid rise in e-commerce and the pressures of urbanization, questions arise regarding how to increase the sustainability of freight transportation while minimizing costs, managing time pressure, and addressing the challenges posed by an aging workforce. The primary research questions this paper aims to address include exploring how UAV technology can improve the efficiency of last-mile deliveries in urban areas and identifying the critical challenges that need to be overcome for widespread adoption.

Customer loyalty highly depends on delivery time, especially in so-called "last-mile deliveries", i.e., deliveries over very short distances, for which the evolution of UAVs will increasingly be able to meet such growing demand. Furthermore, last-mile deliveries represent the majority of shipping costs (around 53%, source businessinsider.com), and are therefore an element where cost reduction is critical.

Recently, UAVs, known as drones, have become an alternative means of package delivery. In terms of establishing a legal framework, we are beginning to take several steps forward. For example, in Europe, starting from January 1, 2021, drone operators are allowed to use their fleets in populated areas, after publishing a framework that allows operations in urban environments classified as medium risk (for example, parcel deliveries, line inspection railways and electricity, supplies of emergency products such as medical equipment and vaccines). Also, in China, this regulation came into force on January 1, 2021. The government has formulated standards for express delivery services by UAVs with a maximum load weight of 150 kg and speed not exceeding 100 km/h, specifying conditions, procedures, risk assessment, etc. However, there are still significant technological and infrastructure limitations to address. The limited load capacity of drones prevents the transportation of goods above a certain size and weight, making them unsuitable for all types of deliveries. Additionally, the challenge of finding landing spots for drones in densely populated urban areas complicates their practical application. Existing literature extensively discusses these technological and regulatory challenges, but a more critical analysis reveals gaps in addressing the integration of UAVs into existing logistics systems, the need for infrastructure adaptation, and the potential societal impacts of widespread drone use.

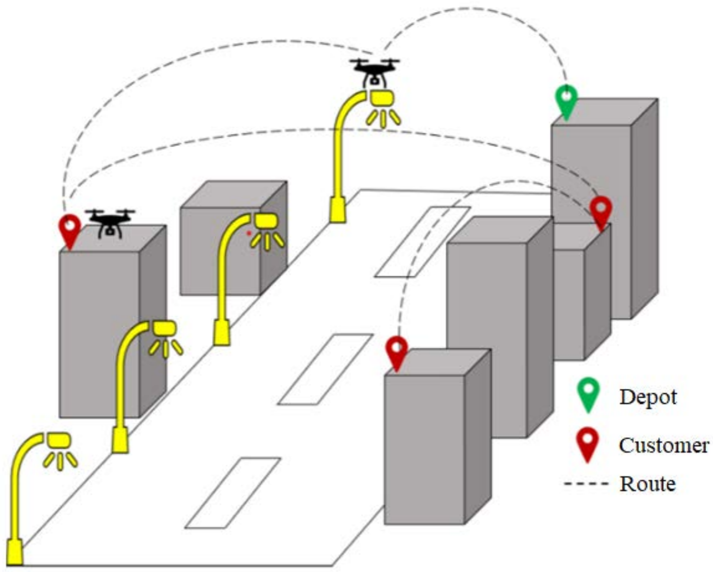


Figure 1. ULM delivery system illustration showing last-mile methods like drones and rickshaws [2]

According to Morgan Stanley, the first massive application of VTOL vehicles will concern the B2B (Business to business) or B2C (Business to client) delivery of loads weighing less than 25 kg on average. Initially, there will be a phase in which their use will be limited to medical supplies and disaster relief, and we already have examples of this type today. Zipline, a US drone operator specializing in the delivery of medical cargo, flew its fleet over 1 million kilometres, making over 13,000 deliveries in Rwanda, transporting 35% of blood samples for transfusion.

Ghana has also started providing coronavirus test kits. In the UK, Skyports, an English start-up, began delivering personal protective equipment between hospitals in Scotland in 2020 to fight COVID-19, also establishing itself as the country's first BVLOS operation. However, there remains a gap in the literature concerning the large-scale economic viability and environmental impact of UAVs in last-mile delivery.

Polaris Market Research, an American research and consultancy company, hypothesizes that the global market for medical drones should reach almost a billion dollars by 2027 (the value in 2019 stood at 110.9 million dollars), with a CAGR in the period 2020-2027 of 31.6%. Subsequently, we will see the first mass application of these aircraft to deliver parcels in rural areas, which is already being witnessed in exceedingly small doses. The current last-mile delivery system is strongly influenced by the density of the delivery network, and in non-urban areas, the density is not such as to often allow prices similar to those in urban areas. Future research should focus on these non-urban applications and examine the scalability of drone logistics in both rural and urban contexts.

Recently, major companies have started using drones to deliver parcels for their customers, e.g. Amazon, DHL, Alibaba, and Japan Post [3]. Despite these developments, further research is needed to explore the optimization of UAV delivery networks and their integration with traditional delivery systems to maximize efficiency and reduce costs.

The paper is structured as follows: Section 2 covers the impact of drones on delivery operations, Section 3 outlines the main models and methods, Section 4 provides a brief discussion of the results, and Section 5 contains the conclusions.

2 Impact of the Drone on Delivery Operations

2.1 Drones Applied for Urban Last-Mile Deliveries

Drones applied for urban last-mile deliveries (Figure 2) are typically restricted to carrying only a single shipment at a time. Therefore, in any case, where considerable quantities of shipments are to be accommodated, a significant increase in the size of the feet of drone landing legs and launching pads may be necessary, raising some crucial questions as to whether drones can actually contribute to the handling of large volumes of parcels, as well as in terms of a significant reduction in logistics costs.

On the positive side, drones are electrically powered, allowing for quick, unobstructed air travel, and they operate autonomously, with minimal human oversight. These features make drones well-suited to improving key performance indicators such as sustainability, cost efficiency, and workforce relief—especially in light of an aging labor force.

This is confirmed by the research report of the EU-Project AURORA (Safe Urban Air Mobility for European Citizens) H2020, which is entitled "D1.2-UAM Sustainable Mobility Indicators Report", where some of the research partners tried to elaborate a set of key performance indicators assessing the impact of air mobility for future sustainable urban mobility planning, or SUMP, which is a strategic and integrated planning process sponsored and designed by the EU Commission to satisfy the mobility needs of people and businesses in European cities and their surroundings for a better and healthier quality of life for citizens [4].

Figure 2. Drone flying with a parcel, in the little pic, and a close-up image of the last Amazon model [5]

2.2 SUMP Principles and Key Indicators for Sustainable Urban Mobility

Each of the SUMP planning activities is fundamentally based on eight principles belonging to the corresponding pillars of sustainable mobility, as listed below:

- Emissions of greenhouse gases;
- Air polluting emissions;
- Energy efficiency;
- Noise hindrance;
- Traffic safety;
- Congestion and delays;
- Net public finance;
- Resilience for disasters and ecological/social disruptions.

In terms of the level of emissions, drone-assisted delivery means less local pollution. Nevertheless, to date, it is not fairly clear whether this assessment is carried out at a global level and considering the entire life cycle.

2.3 Energy Efficiency and Congestion Mitigation

As for the energy efficiency level [6], UAM is less energy effective compared to ground transportation, but it is expected to become more competitive with further development of UAM services. This is primarily due to advancements in battery technologies and drone design, which can enhance overall energy consumption per shipment.

From a congestion perspective, the impact seems positive but minimal due to the limited load capacity of each drone compared to traditional road transport. The ability to bypass traffic may reduce road congestion in urban areas; however, the contribution remains relatively small unless the fleet size is significantly increased.

2.4 Financial Feasibility, Safety, and Noise Considerations

Finally, no clear evaluation is possible for the financial feasibility of the system, for the variation in security, noise emissions, and road safety [4]. While noise hindrance is a concern for residents, particularly in densely populated urban areas, it is essential to develop standardized measurement tools to accurately assess noise emissions for UAM.

Future studies could also explore mathematical models to evaluate these aspects in a more structured way. For instance, multi-objective optimization models could be applied to balance drone route efficiency with noise reduction or fuel consumption. Additionally, algorithms that optimize drone delivery routes while minimizing energy usage could be developed.

3 Models and Methods

While numerous studies have addressed the drone delivery problem [7–9], they are often framed as single-objective optimization tasks. Multi-objective models have been introduced for the vehicle routing problem (VRP), with reviews available in studies [10, 11] and a practical application presented in the study [12].

Despite this, most current models are formulated with a single-objective approach. In practice, however, drone delivery scheduling involves multiple objectives that shippers must achieve. Some proposed systems [13] consider scenarios where drones can visit multiple locations before returning to the depot. However, as noted in the introduction, a drone typically transports only one package at a time.

To reflect this, we redefine the problem to involve drones carrying one package per trip, returning to the depot before serving the next customer. Additionally, drone delivery operations may encounter unexpected issues, such as breakdowns or failed take-offs, which can significantly impact scheduling. Therefore, we propose a multi-objective, three-stage stochastic optimization model in this paper. The model's objectives are as follows:

1) Minimize total delivery cost;
2) Minimize the rate of unsuccessful deliveries;
3) Maximize the reward for on-time deliveries.

For the second objective, unsuccessful deliveries occur when a drone cannot take off from the depot or breaks down end route. Instead, for the third objective, customers may specify preferred time slots for package delivery. We evaluate the logistics system's performance using real data from Singapore's delivery services, encompassing forty customers and two drone depots, as illustrated in Figure 3 [3].

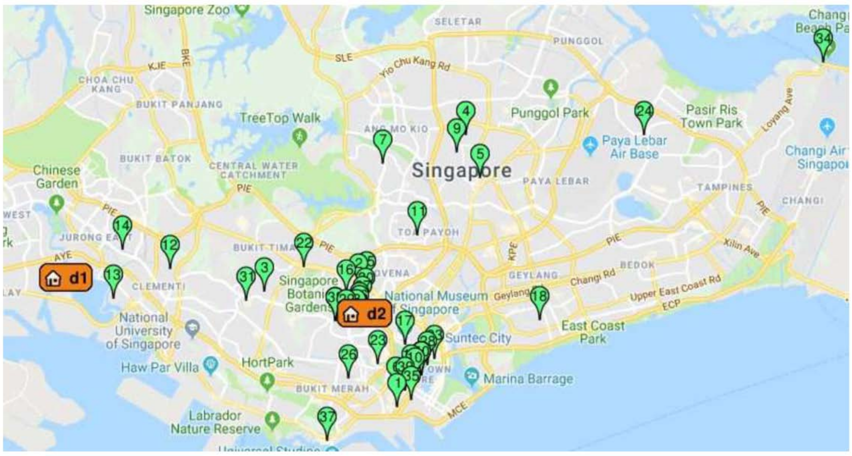


Figure 3. Example of customer and drone depot locations in Singapore case study [3]

In general, drone delivery can be seen as a chain Depot-Drone-Client Home, but due to the short distances covered by actual drones, drone delivery from a Central Distribution Point (CDP) requires a complex and dense depot network. Wang et al. [14] study the Vehicle Routing Problem with Drones (VRPD) with a worst-case scenario, analysing its use bounds on maximal savings to the companies. Instead, Poikonen et al. [15] compare different drone types to understand the trade-off, for example, between a greater number of slower drones or a smaller number of faster ones.

Boysen et al. [1] analized the VRPD at the three typical logistics planning levels, composed of strategic, tactical, and operational planning. At the strategic level, the focus is on setting up the infrastructure, that's to say, where to locate the depots from where the drones are launched (the depot network), verifying the trade-off between a greater number of depots (increasing the possibility of reaching customers) and the reduction in investment costs. Sharavani et al. [16] introduces, in the network design, a fuzzy system to consider the typically variable location of the customers. The tactical level consists of staffing and fleet sizing. Troudi et al. [17] study the establishment of a mixed-MIP whole program to minimize the drone fleet considering customers' time frames. Finally, the operational level involves routing and scheduling phases, including different types of vehicle routing algorithms, and also integrating the possibility of adding to the logistic network the recharging stations where drones can recharge their batteries autonomously. Sometimes, sensitivity analysis of the delivery system is conducted, altering input parameters to stress the mathematical model. For example, a Pareto frontier analysis was carried out based on two main objectives: minimizing total costs (from an economic perspective) and minimizing the percentage of unsuccessfully delivered parcels (from a quality-of-service perspective) (Figure 4) [3]. As shown in the graph in Figure 4, even within the example cited, there is a compromise between using drones and outsourcing deliveries to external couriers. This helps the shipping company avoid exceeding cost thresholds, allowing it to make tactical decisions that serve the entire distribution map while adhering to schedule constraints.

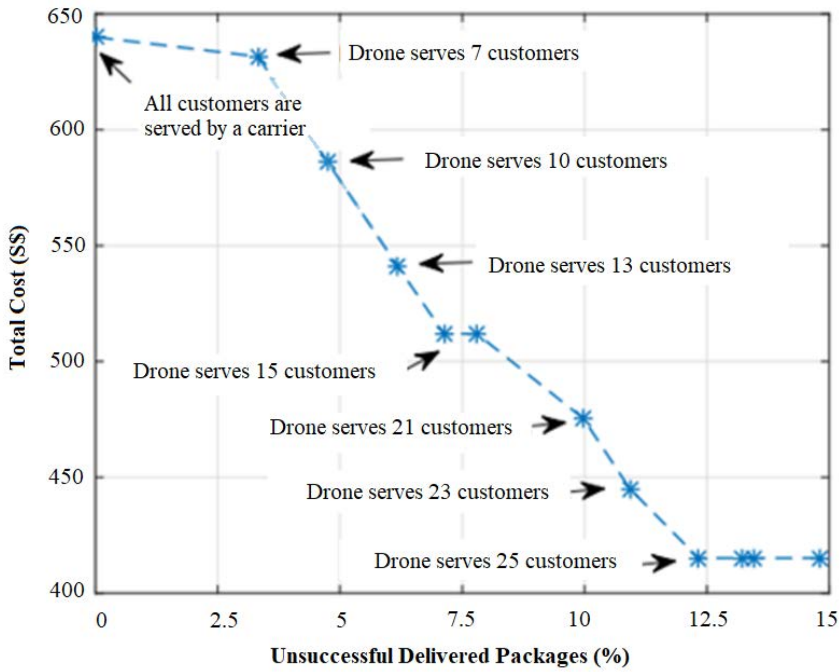


Figure 4. The Pareto frontier among economics vs quality of service of a drone-assisted delivery system [3]

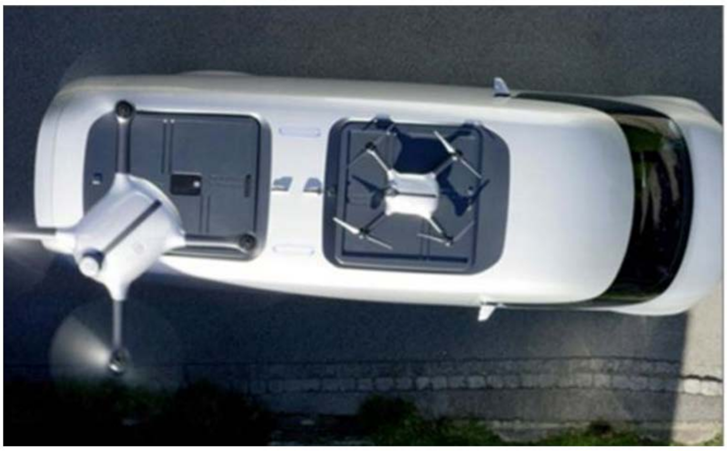


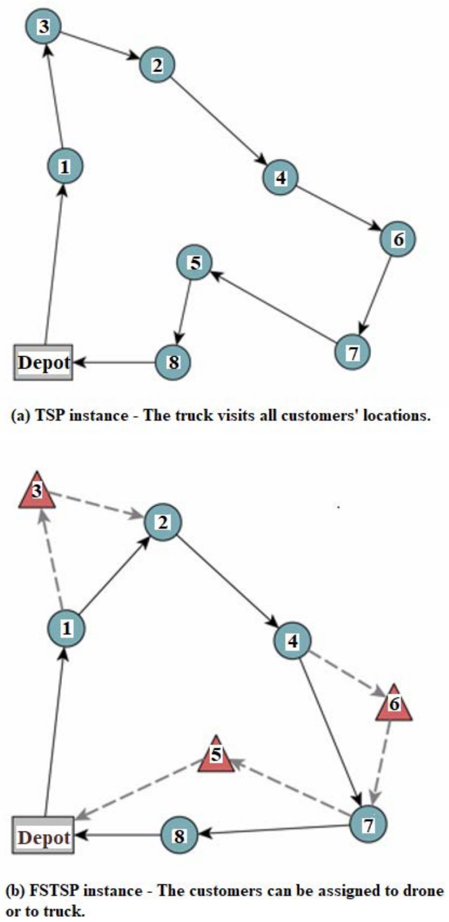
Figure 5. Drone launched from a van equipped with two landing pads [18]

As can be seen from the graph shown in Figure 4 above, even framed in the previously cited example, there is a sort of compromise between the use of drones and the choice of outsourcing the delivery of the goods to an external courier to help the shipping company not to exceed the cost thresholds and consequently make the logistics company capable of making its own tactical decisions, serving both the whole delivery distribution map, and respecting the assigned timesheet schedule constraints.

Drones indeed present promising benefits in terms of reducing operational costs and enhancing customer service efficiency. However, due to their limited payload capacity and restricted flight range, they are unable to completely replace conventional delivery trucks. A recent last-mile delivery concept introduces the use of delivery vans as mobile launch platforms for drones, creating a new delivery chain: Depot-to-Van-to-Drone-to-Customer's Home (as shown in Figure 5) [1].

Regarding this research topic, in their pioneering article, Gonzalez-R et al. [19] introduced the possibility for the truck to wait for the drone to return to the point where it was launched, allowing multiple deliveries for each single and distinct "drone launch" mission.

Later, Murray and Chu [20] adopted an alternative approach, proposing what is known as the Parallel Drone Scheduling Traveling Salesman Problem (PDSTSP). This model introduced a new way of considering drone and truck delivery operations by treating them as independent processes. In the PDSTSP framework, a drone is dispatched from a depot to deliver packages to assigned clients and then returns to the depot, operating separately from the truck's delivery route. Meanwhile, the truck undertakes its own delivery circuit, serving a different set of clients. The novelty of the PDSTSP lies in the separation of these two delivery modes, allowing them to function in parallel. By decoupling the drone's and the truck's routes, the approach enables greater flexibility in assigning clients to either delivery mode based on specific requirements or constraints. The model categorizes clients into two clusters—those designated for drone delivery and those that the truck will serve directly. This clustering is then subjected to mathematical analysis to optimize delivery efficiency within each group, while also examining the overall system performance. This approach provides valuable insights into how independent yet concurrent delivery systems can enhance logistical efficiency and reduce total delivery time.



(a) TSP instance - The truck visits all customers' locations.

(b) FSTSP instance - The customers can be assigned to drone or to truck.

Figure 6. Deliveries are made either by truck following a traditional TSP route (a) or by a truck and drone working together in an optimal FSTSP combination (b) [21]

Instead, in the Flying Sidekick Traveling Salesman Problem, or FSTSP, truck and drone work collaboratively, and the following Figure 6 shows the underlying concept of truck and drone delivery integration. This mixed delivery modality can be extremely useful for cases where there are isolated or difficult-to-reach by-road network customers.

While the traditional and popular Traveling Salesman Problem, or TSP, searches for the best route for only one vehicle delivering goods to a set of selected customers (subgraph (a) of Figure 6), the flying sidekick traveling salesman problem (FSTSP) consists of finding optimal routes for both a drone and one road vehicle making an integrated service that uses the synergistic advantage of two coupled vehicles, trucks and drones. This way, the long autonomy and high capacity of the truck combine with the high mobility and low trip costs of the drone [21, 22].

The delivery truck leaves the depot loaded with both the customer parcels and the drone. When the truck makes a stop to deliver packages, the drone is deployed from the truck to deliver a package to a specific customer.

After delivering the goods, the drone returns to the truck and lands on it during a road delivery stop. Therefore, the FSTSP consists of simultaneously finding the optimal routes for both a drone and a road vehicle by providing an integrated service that exploits the synergistic advantage of two vehicles, trucks and drones (subgraph (b) of Figure 6).

Murray and Raj [22] expanded upon the original Flying Sidekick Traveling Salesman Problem (FSTSP) by developing the Multiple Flying Sidekicks Traveling Salesman Problem (MFSTSP). This extended model involves a delivery truck working in tandem with a fleet of drones. In this scenario, the drones are deployed directly from the truck, each carrying out a single-item delivery before returning to the truck. Once back, the drones recharge their batteries and can be reloaded for subsequent delivery tasks [23].

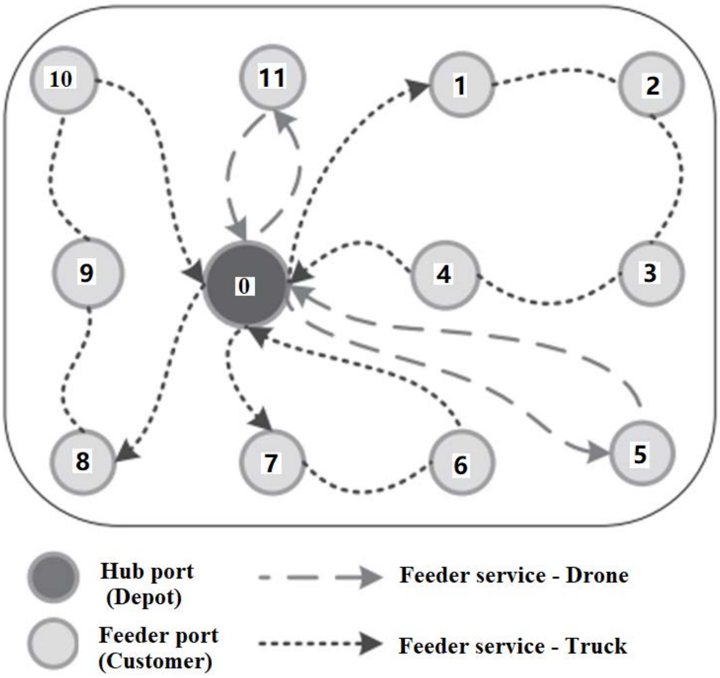


Figure 7. Maritime network as a dual-carrier hub-and-spoke model for small (drone) and medium (truck) ships [24]

An alternative approach to cope with two different kinds of customers can be derived by adapting the hub-and-spoke network model to understand the so-called feeder-bus network design problem, or FBNDP [25, 26].

The original model is addressed to the network optimization problem of bus lines feeding a given number of rail stations, which are located along a railway line operating with a known train frequency [25].

As recently as the last decade, the FBNDP has also been applied to the network design of low-volume short-sea containerships (Figure 7 by solving the optimal configuration of their maritime transportation and shipping service network, which was represented by the connections from the hub ports to the regional ports that constitute the feeder network that is serviced by small-sized or medium-sized feeder containerships [24]. This corresponding problem was solved in the particular case of the feeder service operating in the Black Sea region, in order to determine both the optimal size of the feeder ship fleet and the mix between routes and travel times while minimizing logistics costs for a given horizon of planning.

4 Discussion and Summary of Results

This short section summarizes and discusses the results of the previous sections. As regards the multi-objective optimization and drone scheduling, a comprehensive analysis of the results from the proposed multi-objective model reveals significant trade-offs between cost minimization, on-time delivery rewards, and the percentage of unsuccessful deliveries. The stochastic nature of the drone scheduling model, accounting for potential breakdowns or failed take-offs, demonstrates the need for robust planning and the inclusion of backup systems to minimize service disruptions.

Moving on to the Sensitivity Analysis and Pareto Frontier; further sensitivity analysis, including the Pareto Frontier study, illustrates the complex relationship between cost and service quality. Figure 4 clearly shows that when outsourcing delivery services, total costs rise slightly but unsuccessful delivery rates drop, suggesting that hybrid solutions combining drones and traditional couriers can yield optimal outcomes for the last-mile delivery network.

Finally, as concerns Real-World Application and Policy Implications; based on real-world data from Singapore's delivery network, the results indicate that while drones contribute to reducing operational costs, integrating them with mobile launching platforms such as delivery vans (Figure 5) or optimizing the depot network through strategic location planning further enhances system efficiency. Policymakers and logistics companies may need to consider dynamic and flexible depot networks for future implementations.

5 Conclusions

The field of drones used in last-mile delivery is always ongoing research. The already commercial existing operative drones (used by Amazon and other commercial companies) are simple depot-to-customer-to-depot delivery types. However, our research aims to advance this field by focusing on novel mixed-mode delivery strategies that enhance current operational models. The future will be a mixed delivery of trucks and drones called Flying Sidekick Traveling Salesman Problem (FSTSP), which allows integration of the greater capacity of a truck with the flexibility and speed of drones. Future research efforts on this topic shall consider the total integration of drones and trucks [23], avoiding long waits for the drones to return or for the delivery of the truck (with its stop period) through setting up suited operation strategies addressed to integrate the two delivery services. This integration highlights the significant potential for operational optimization, filling a crucial gap in existing literature.

It should also be underlined that the field of feeder systems of passenger transit and goods distribution has had in the past and continues to have several relevant academic interests, encouraging practical attempts to transfer it to optimal system design and management of some drone-based delivery instances. More recently, another future research project regards the real-time optimization of the mixed routing due to delays caused by road congestion or issues found in drone delivery. Real-time adaptation mechanisms could address current operational inefficiencies, offering a robust solution to dynamically changing urban logistics conditions.

Considering the increasing number of drones flying daily, there are several research perspectives in the cyber-security field that are directly linked to the growing need for secure communication protocols and information and data sharing among these devices and control units [27]. Drones require protection in terms of flight safety and the securing of data exchanges, two mandatory aspects given the importance and considerable usefulness of the uses that drones have in normal civil real life, thus guaranteeing both the success of the mission and serving as a reference guide to preventing severe incidents or unprecedented cyber-attacks [28]. Thus, cybersecurity becomes a key research frontier, essential not only for the success of individual deliveries but also for securing the broader infrastructure supporting drone-assisted logistics.

Last but not least, to allow the operation of drones in urban centers, many countries around the world should modify and adapt their current national standards, flight rules, and aeronautical legislation on unmanned aerial vehicles, i.e., UAVs, which today generally prohibit any type of drone flight in any inhabited context, as well as the carrying out of any real operational simulation test in the field. Future research could focus on policy recommendations and legal frameworks, ensuring that the integration of drones into urban logistics is both practical and scalable. Furthermore, more simulation studies will be required to overcome the operational restrictions imposed by current regulations.

In conclusion, this research not only advances current drone delivery models but also emphasizes critical areas like real-time optimization, cybersecurity, and regulatory changes, all of which are pivotal for the future success of drone-assisted logistics systems.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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