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Collaborative optimization of urban drone and public transit integration

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Abstract. The efficient and cost-effective delivery of goods ordered online poses a significant challenge in the field of logistics. Many companies are exploring the use of drone technology to streamline delivery times and expenses. In the context of last-mile deliveries, the deployment of drones represents a promising technology that offers environmental and economic advantages. This study focuses on last-mile delivery systems, where a fleet of drones operates in conjunction with public transportation to fulfill customer orders. To address this issue, the paper expands upon a mathematical model based on the Vehicle Routing Problem (VRP). Furthermore, it presents a real-life scenario inspired by Stanford's transportation paradigm. The findings indicate that optimizing the sequence for visiting customers and public transportation stations has a substantial impact on both remaining power and time efficiency during drone deliveries. Moreover, leveraging public transport vehicles for recharging drones or approaching customers can reduce the required number of drones within service areas, thereby extending their operational lifespan. These results highlight the potential for using public transportation as a mobile charging station to save energy and improve package delivery efficiency in last-mile drone deliveries.

Keywords: urban logistics, drone-public, path optimization.

1. Literature Review

The surge of e-commerce and the rapid urbanization have injected fresh vigor into the development of e-commerce, driven by novel business models such as customer live e-commerce, community group buying, and social e-commerce. This has led to a shift in consumer behavior from business-to-business (B2B) to business-to-consumer (B2C), with heightened expectations for delivery services [1]. In recent years, express delivery volume has maintained an annual growth rate of approximately 30%, attributed to increasing market demand and policy incentives. It is anticipated that the total postal and express delivery volume will sustain an annual growth rate of around 6.3% from 2021 to 2035 [2]. Of course, this continued expansion will necessitate greater demand for last-mile delivery vehicles, making it imperative for traffic management authorities to ensure the healthy and sustainable development of the express delivery industry while upholding traffic safety standards [3].

Therefore, escalating urbanization worldwide has posed significant challenges in delivering goods. Moreover, rural areas heavily rely on manual labor for deliveries due to remote locations and scattered orders resulting in low efficient and high costs [4]. Most final mile deliveries are carried out using electric tricycles, weak safety education among logistics companies regarding their use leads to frequent accidents such as speeding or overloading during production processes [5]. At the same time, operational expenses within current enterprises is rising [6].Drones as a new mode of transportation offers economic advantages through flexible three-dimensional movement capabilities which can bypass traffic jams or accidents leading to faster average speeds and reducing overall delivery times [7]. From an environmental perspective drones offer reduced carbon footprint compared with typical diesel deliveries owing largely due their electric engine propulsion systems [8].Accordingly drone technology presents substantial commercial opportunities indicated by its projected global market size reaching $1.33 billion by 2030 with compound annual growth rate at 14%.[9].

In the context of new retail, e-commerce logistics distribution faces challenges in matching supply and demand. Consumers expect door-to-door delivery services to enhance convenience and user experience. However, traditional end-of-line distribution methods hinder e-commerce development due to poor timeliness and limited convenience [10]. As a result, alternative delivery methods are necessary. Wang highlighted the potential of drones for their flexibility, cost-effectiveness, and suitability for various civil applications, particularly in package delivery within the logistics industry. Traditional vehicle-based parcel delivery is constrained by road conditions and geography, leading to high distribution costs (fixed vehicle costs, labor costs) [11]. In contrast, drones can bypass ground constraints such as traffic congestion or complex terrain while flying shorter routes without additional waiting time due to traffic jams. Experimental simulations have demonstrated that using drones for last-mile logistics reduces fixed costs and fuel consumption compared to traditional transport vehicles [12].In contrast with prior research efforts, this study focuses on leveraging existing public transportation systems as mobile recharging hubs for extending drone flight ranges. Pioneering work from Stanford University introduces novel approaches utilizing modes like buses within these networks to enhance unmanned aerial vehicle capabilities [13]. The development includes an intricate algorithmic structure addressing multi- drone cargo deliveries through integration with bus services aimed at conserving drone energy resources [14]. Generally speaking, substituting traditional truck-based methods with utilizing forms of mass transit like commuter trains or trams offers dual benefits for expanding drones operational distances [15].

In recent years, traffic restrictions in urban areas have efficient improvement in drone joint delivery models due to peak congestion characteristics associated with urban trucks. Conversely public transport priority policies have facilitated efficient operation during rush hours within public transportation systems [13]. Y. Liu recently studied utilizing public transportation networks for expanding flight coverage in drone package deliveries while other forms of public transport with drones demonstrating increased customer distribution rates compared with standalone drone operations [16]. Energy efficient utilization across existing public transportation networks extending operational range through bus-assisted charging stations as depicted. This approach not only expands service coverage but also reduces overall costs while prolonging drone service life. Firstly, independent routing characteristic of mass transit systems ensures efficient unaffected by urban traffic patterns leading to improved delivery timelines and reduced energy consumption levels; secondly these established infrastructures are essential components supporting urban mobility needs thereby presenting cost-effective alternatives compared with constructing new facilities like charging stations envisioned within smart city frameworks while also minimizing reliance on conventional fuel-powered vehicles.

2. Methodology

2.1. Problem description and assumptions

This section describes the main assumptions of the defined problem and presents the associated mathematical model. It is assumed that a regional parcel delivery system consists of several distribution

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warehouses equipped with a certain number of drones, several bus routes available for drone pick-up equipped with a number of vehicles, and a number of customer points with demand. At the beginning of the delivery, the bus vehicles run according to a fixed line and a fixed schedule, and the drones depart from the warehouse to carry the bus vehicles and run with the buses, and at the optimal location from the customer point, the drones take off and deliver to the customer point, and after delivering customers in a region, the drones can proceed to provide service to the next customer or go to a nearby station to carry the buses back to the warehouse. The objective function of the problem aims to minimize the total energy required to deliver customer orders in the last mile. These established infrastructures are essential components supporting urban mobility needs thereby presenting cost-effective alternatives compared with constructing new facilities like charging stations envisioned within smart city frameworks while also minimizing reliance on conventional fuel-powered vehicles, as shown as **Figure 1**.

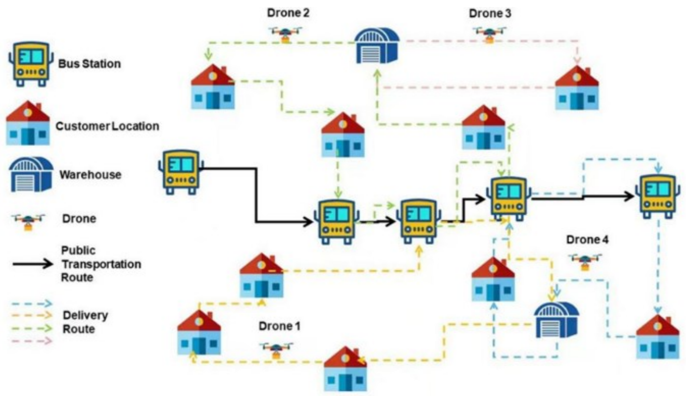

Figure 1. General description of the proposed Drone-public delivery system.

2.2. *Notations and mathematical formulations*

This study investigates the application of drones in less developed areas logistic systems. We introduce a variable to record the time-space arc selection for drone d, as follows; x_{ij}^{d} =1 if drone v flies from node i to node j, SoC state of charge, e.g., 100%.The planning horizon is discreted by T=[t0, t0 +Δ, t0+2Δ,...,T], Ns =S∪W∪C, N={(n, t)|n∈Ns, t∈T} time-space nodes set example : N={0:(warehouse 1, 8:00), 1:(0, 1), ... },i, j∈N, Ni− the feasible downstream node for node i, i∈N, e.g., i is defined as (n1, t1), j is defined as (n2, t2). j∈Ni−→t2 >t1.t2 >t1 and n1=n2→j∈Ni−. Rn1,n2 is the route distance between n1 and n2. Dn1,n2 is the distance between n1 and n2, if min$\{\frac{R_{n_1,n_2}}{v_{\max}^{B}}, \frac{D_{n_1,n_2}}{v_{\max}^{v}}\}$> t2−t1 , then j ∉ Ni− , Ni+: i∈Nj+ ↔j∈Ni−, arc a=(i, j), ∀i, j∈N. FS records the spatial node for node i∈N, such that FS (i)∈Ns .FT records the time for node. i∈N, such that FT(i)∈T. FE records the minimum energy for spatial node FS(i), i∈N to node FS(j), j∈N within the time period (FT(j)−FT(i)).FE records the minimum energy for spatial node. FE records the minimum energy for spatial node FS (i), i ∈ N to node FS (j), j∈N within the time period (FT(j)−FT(i)). FE records the minimum energy for spatial node.

2.3. *Drone energy consumption models and constraints*

Dorling et al. verified that the average power consumption of a drone is approximately equal when hovering, flying horizontally and changing altitude. Therefore, the battery consumption is positively correlated with the weight of the drone. In this study, we refer to Liu’s energy consumption model and introduce the parameter α denotes the rate of energy consumption per unit of distance per unit of weight, and denote own weight by ws, wdi is the loaded weight of the drone when it leaves the point i. d is the distance from I to j. The energy consumption of the UAV d passing through the (i, j) is then expressed.

$$F_{dij} = \alpha(w_s + w_{di})d_{ij} \tag{1}$$

The energy consumption of the drone passing through (i, j).

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$$Minimize \sum_{i\in W,C}\sum_{j\in J} \quad \sum_{d\in D} F_E \ \ x_{ij}^d + \sum_{i\in B}\sum_{j\in W,C} \quad \sum_{d\in D} F_E \ \ x_{ij}^d \tag{2}$$

The objective function (2) aims to minimize the total energy that drones consumed in delivery operations. As drone traveling over the bus does not endure energy consumption to drones, it is not included in the objective function.

$$Minimize \sum_{d\in D} F_T \ \ x_{ij}^d + \sum_{i\in B}\sum_{j\in J} \quad \sum_{d\in D} F_T \ \ x_{ij}^d \tag{3}$$

The objective function (3) aims to minimize the total time consumed in delivery operations.

3. Results

The model was validated by gathering actual parameters of customer and bus stop distribution in Suqian, China. Figure 2 illustrates the service regions utilized for distribution operations. Selecting several bus routes (No. 101,102,103) and establishing 13 strategically located bus stops extended the drone's flying distance by enhancing battery life. Detailed information on the selected bus routes includes starting and ending locations, frequency, route length, as well as first and last departure times.

Notably, more than the chosen routes exist within the study area; however, these three lines were selected due to their even distribution throughout the region. The model facilitated parcel delivery services for 30 customers based on real-world conditions. Two warehouses were established as freight stations with multiple drones at each location distributed across Suqian city to initiate delivery operations. Each customer had specific demands which necessitated a regional parcel delivery system comprising multiple distribution warehouses with a specified number of drones, three drone-ready bus routes equipped with various vehicles, and numerous customer points requiring deliveries of parcels with varying weights. Furthermore, it is emphasized that testing the validity of this model requires studying different input parameters including warehouse locations while also considering changes in both customer numbers and weight limits imposed on drones alongside their energy constraints. this model requires studying different input parameters including warehouse locations while also considering changes in both customer numbers and weight limits imposed on drones alongside their energy constraints.

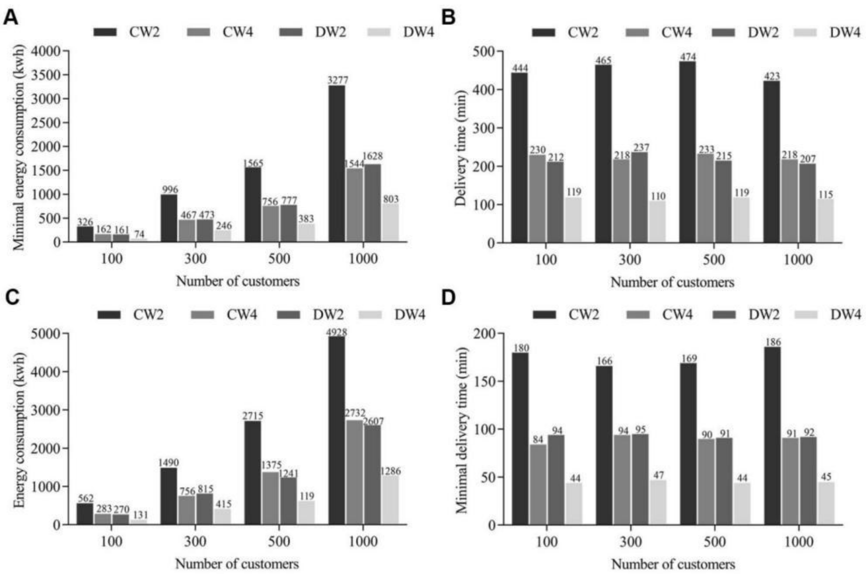

Figure 2. Numerical comparison.

In China's retail sector Meituan has initiated drone shuttle deliveries between skyscrapers using fourth- generation small multi-rotor drones similar to those described in this paper which support temperatures ranging from -20°C to 50°C.Sample problems are solved using Python software running on an Intel® Core™ i7 6100 CPU @3.7 GHz8 GB memory system.

This paper studied the optimal delivery route and order allocation for drones by solving the mixed integer linear programming (MILP) model that was formulated. Figure 3 shows the best solution obtained from numerical experiments. For example, the drone delivery route includes starting from the warehouse, jumping on a bus to travel two stops to charge the battery and passing through other stops, and then taking the bus to travel three stops back to the warehouse. According to the assumption, the drone can fully charge its battery in two stops. Therefore, the purpose of continuing to take the bus is to reach the customer without consuming energy, which highlights another role of public transportation in improving delivery operations. The results show that the order in which the drone visits the bus station and the customer.

The study was conducted with four different numbers of customer totals of 30, 100, 500, and 1,000. After the model is solved, firstly, the total number of drones launched from each warehouse must fully meet the customer's needs. Secondly, the total number of public transportation stops used by drones in each warehouse to complete delivery operations in the assumed service area. Finally, the total energy consumption and time of drones in the delivery process. Under the premise of meeting the load capacity of drones, the warehouse closest to the public transportation infrastructure will maximize the load capacity of drones and complete the last-mile delivery. Even from the perspective of energy consumption, this conclusion is reliable. In the case of two warehouses, the position of the warehouses changed from a concentrated state to a dispersed state, serving different numbers of customers, and the energy consumption was reduced by 50.6%. In the case of four warehouses, the energy consumption was reduced by 47.7%. Compared to dispersed warehouses, drones delivering packages in concentrated warehouses require more energy, but it should also be noted that in urban areas with high package demand and short-distance delivery, drones fly alone for a longer distance. When the total number of warehouses increases from 2 to 4, the energy consumption reduction rate in the centralized warehouse scheme ranges from 42.8% to 50.6%, and the energy consumption reduction rate in the decentralized warehouse scheme ranges from 50.6%. Therefore, since the public transportation network plays an important role in distributing parcels, increasing the number of warehouses will not cause a significant change in energy consumption.

The integration of drone delivery with public transportation as a mobile charging station is proposed to address the limitation of flight distance. Leveraging public transportation reduces delivery time and energy consumption by allowing drones to recharge their batteries and reach nearby customer locations. Therefore, it is necessary to consider using pre-build urban infrastructure, such as transportation system infrastructure and the optimal number of drones, rather than building more facilities such as warehouses or charging stations to fully cover the service area. This study presents a comprehensive analysis of the utilization of drones in “last-mile” delivery, focusing on economic and environmental considerations. The integration of drone delivery with public transportation as a mobile charging station is proposed to address the limitation of flight distance. Leveraging public transportation reduces delivery time and energy consumption by allowing drones to recharge their batteries and reach nearby customer locations. A mixed integer linear programming optimization model is introduced for planning drone group trips to fulfill customer orders, validated using real-world data from real node in China. Future research directions include developing heuristic meta-heuristic algorithms for large-scale problem solving, integrating drone-supported last-mile delivery into smart city scenarios, and exploring product overlap among warehouses in multiple picking scenarios.

References

[1] Choi, Y., & Schonfeld, P.M. (2017). Optimization of Multi-package Drone Deliveries Considering Battery Capacity.

[2] Yoo, H. D., & Chankov, S. M. (2018). Drone-delivery using autonomous mobility: An innovative approach to future last-mile delivery problems. In *2018 IEEE International Conference on*

Industrial Engineering and Engineering Management (IEEM) (pp. 1216-1220). https://doi.org/10.1109/IEEM.2018.8607829
[3] Kuru, K., Ansell, D., Khan, W., & Yetgin, H. (2019). Analysis and optimization of unmanned aerial vehicle swarms in logistics: An intelligent delivery platform. *IEEE Access, 7*, 15804-15831. https://doi.org/10.1109/ACCESS.2019.2892716
[4] Murray, C. C., & Chu, A. G. (2015). The flying sidekick traveling salesman problem: Optimization of drone-assisted parcel delivery. *Transportation Research. Part C, Emerging Technologies, 54*, 86-109. https://doi.org/10.1016/j.trc.2015.03.005
[5] Poikonen, S., & Golden, B. (2020). Multi-visit drone routing problem. *Computers & Operations Research, 113*, 104802. https://doi.org/10.1016/j.cor.2019.104802
[6] Chung, S. H., Sah, B., & Lee, J. (2020). Optimization for drone and drone-truck combined operations: A review of the state of the art and future directions. *Computers & Operations Research, 123*, 105004. https://doi.org/10.1016/j.cor.2020.105004
[7] Song, B. D., Park, K., & Kim, J. (2018). Persistent UAV delivery logistics: MILP formulation and efficient heuristic. *Computers & Industrial Engineering, 120*, 418-428. https://doi.org/10.1016/j.cie.2018.05.013
[8] Dorling, K., Heinrichs, J., Messier, G. G., & Magierowski, S. (2017). Vehicle routing problems for drone delivery. *IEEE Transactions on Systems, Man, and Cybernetics. Systems, 47*(1), 70-85. https://doi.org/10.1109/TSMC.2016.2582745
[9] Jeong, H. Y., Song, B. D., & Lee, S. (2019). Truck-drone hybrid delivery routing: Payload-energy dependency and no-fly zones. *International Journal of Production Economics, 214*, 220-233. https://doi.org/10.1016/j.ijpe.2019.01.010
[10] Kirschstein, T. (2020). Comparison of energy demands of drone-based and ground-based parcel delivery services. *Transportation Research. Part D, Transport and Environment, 78*, 102209. https://doi.org/10.1016/j.trd.2019.102209
[11] Choudhury, S., Solovey, K., Kochenderfer, M. J., & Pavone, M. (2021). Efficient large-scale multi-drone delivery using transit networks. *The Journal of Artificial Intelligence Research, 70*, 757-788. https://doi.org/10.1613/JAIR.1.12450
[12] Kitjacharoenchai, P., Min, B., & Lee, S. (2020). Two echelon vehicle routing problem with drones in last mile delivery. *International Journal of Production Economics, 225*, 107598. https://doi.org/10.1016/j.ijpe.2019.107598
[13] Gonzalez-R, P. L., Canca, D., Andrade-Pineda, J. L., Calle, M., & Leon-Blanco, J. M. (2020). Truck-drone team logistics: A heuristic approach to multi-drop route planning. *Transportation Research. Part C, Emerging Technologies, 114*, 657-680. https://doi.org/10.1016/j.trc.2020.02.030
[14] Wang, D., Hu, P., Du, J., Zhou, P., Deng, T., & Hu, M. (2019). Routing and scheduling for hybrid truck-drone collaborative parcel delivery with independent and truck-carried drones. *IEEE Internet of Things Journal, 6*(6), 10483-10495. https://doi.org/10.1109/JIOT.2019.2939397
[15] Huang, H., Savkin, A. V., & Huang, C. (2020). Scheduling of a parcel delivery system consisting of an aerial drone interacting with public transportation vehicles. *Sensors (Basel, Switzerland), 20*(7), 2045. https://doi.org/10.3390/s20072045
[16] Liu Y., Liu Z., Shi J., Wu G., & Pedrycz W. (2020) Two-echelon routing problem for parcel delivery by cooperated truck and drone. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, *51*(12), 7450–7465.