Scheduling and Routing for Multi-modal Last-mile Delivery under Multiple Uncertainties

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1 INTRODUCTION

Drones offer significant potential for transforming the last mile of urban logistics due to their flexibility, high speed, and cost-effectiveness (Agatz *et al.*, 2018). However, the limited energy reserves and carrying capacity of drones result in relatively low delivery efficiency. To optimize drone usage, a logistics delivery model that integrates truck-drone collaboration—known as the truck-drone mode—has been widely explored in the literature (Li *et al.*, 2021). In this model, the truck acts as a mobile depot, while the drone is employed for last-mile deliveries (Ostermeier *et al.*, 2023). However, the truck-drone hybrid mode has encountered challenges in gaining widespread practical adoption. These challenges are mainly attributed to trucks often being impeded by traffic constraints and the limited carrying capacity of drones. Most drones discussed in the literature have a maximum payload capacity of only 10 kg (Li *et al.*, 2021), (Heimfarth *et al.*, 2022). In addition, the flight duration and range of drones are also easily limited by changing weather conditions. To address these challenges, recent research has explored increased collaboration between tricycles, drones, and trucks to enhance delivery efficiency through multimodal delivery systems (Sluijk *et al.*, 2023), (Chen *et al.*, 2024). However, integrating trucks with a fleet of heterogeneous vehicles introduces additional scheduling complexities, particularly in unpredictable urban environments. For multimodal systems to be effective, it is crucial to account for the distinct characteristics of each modality and to integrate them in a manner that maximize their potential.

Various uncertainties in complex urban environments—such as traffic (Wang *et al.*, 2022), weather (Chen *et al.*, 2023), and GPS errors (Zhao *et al.*, 2022)—significantly impact delivery decisions. While multimodal systems offer flexibility, they introduce added challenges. In tri-modal systems, factors like weather and traffic influence the availability and performance of drones and tricycles, making mode selection crucial. For example, drones can bypass traffic and reduce costs but are highly susceptible to weather, such as high winds that limit range or prevent takeoff. Tricycles, although less affected by weather, are more constrained by traffic. Effective multimodal delivery must address these uncertainties to optimize mode selection. Uncertainty also complicates synchronization between modes. Trucks may face delays from congestion or parking issues, disrupting schedules and meeting points with drones or tricycles, leading to further delays. Weather or traffic delays to drones and tricycles may require trucks to adjust their plans, thus extending delivery times. Severe weather can drastically reduce drone endurance or even lead to crashes, forcing immediate operational halts. In such cases, trucks may need to retrieve stranded drones, causing significant delays and potentially halting deliveries. While minor synchronization risks may only slightly reduce efficiency, neglecting emergency stop risks can lead to severe inefficiencies, potentially making scheduling infeasible and ultimately resulting in synchronization failure.

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Objective. We are interested in investigating the following research questions:

- How can different modes be combined for last-mile deliveries, leveraging their unique features to reduce synchronization risks and enable seamless transportation?
- Can we develop robust and efficient routes and schedules for a tri-mode delivery system?
- How does a tri-mode delivery system perform under various uncertainties compared to existing delivery systems, e.g., truck-drone or truck-only systems?

To better reflect real-world conditions and develop effective scheduling and routing solutions for multimodal delivery systems under uncertainty, **we introduce the Stochastic Heterogeneous Vehicles Scheduling and Routing Problem (SHVSRP), which seeks to optimize the allocation of heterogeneous vehicles to enhance delivery efficiency and minimize synchronization failures.** SHVSRP is a dual-objective problem focused on minimizing both the expected completion time and the risk of synchronization errors. We consider various uncertainties in the urban environment, such as weather and traffic, to develop the robust routes and schedules for last mile multimodal delivery system.

The contributions of this work are: (i) Introducing the SHVSRP for the first time and formulating it as a mixed-integer programming model, (ii) Efficient algorithm to find the optimal routes and schedules, including the optimal number of drones and tricycles, and optimal usage of drones and tricycles, (iii) Performance analysis comparing to single or two-modes systems, and (iv) Operational insights under different settings, such as fleet size, weather conditions, and traffic conditions.

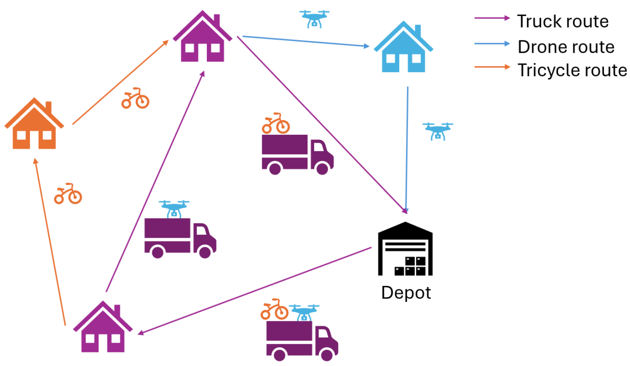

Figure 1 – *An illustration of a truck-tricycle-drone delivery system. The truck equipped with tricycles and drones start at the depot (black warehouse) and then deliver goods to customers. Drones and tricycles will be dispatched to complete service and be picked up at designated nodes.*

2 METHODOLOGY

We consider optimal routing and scheduling of drones, tricycles, and delivery trucks to shape a new paradigm of parcel delivery. In particular, a unique variant of the previous vehicle routing problems is introduced, motivated by a scenario in which uncrewed aerial vehicles (UAVs) and tricycles work in collaboration with a traditional delivery truck to distribute parcels.

We define this as the Stochastic Heterogeneous Vehicle Scheduling and Routing Problem (SHVSRP). Each customer must be served once by either a truck, drone, or tricycle, with some customers restricted to truck-only service (e.g., due to parcel size, signature requirements, or landing limitations). Figure 1 illustrates this system. All vehicles (truck, drone, and tricycle) operate from a single depot and may travel in tandem or independently; in tandem, drones and tricycles conserve energy by being transported by the truck. Once launched, the UAV or tricycle must visit a customer and return to either the truck or the depot within the its endurance limit. The objective of our problem is to minimize the time required to service all customers and return both vehicles to the depot as well as the risk of synchronization between different modes.

Our objective is to minimize the expected total tour duration to serve all customers and synchronization risk, which is quantified by the waiting time of each mode at each node. Mathematically, the optimal objective is the expected arrival time of the last vehicle at the depot $a_{0'} \in \mathbb{R}^+$ and the expected total waiting time at each nodes:

$$t^* = \min E(a_{0'} + \sum \omega_i),$$

subject to several constraints considering uncertainty and feasibility.

This problem can be solved by advanced solver on small instances. To efficiently solve the large scale problem, we propose a parallel 2-phase heuristic approach as shown, which solves a capacitated routing problem without time consideration at the first stage and then solves scheduling problems with fixed feasible capacitated route. The algorithm starts from an initial solution, and then searches for feasible and better routes for routing problems with three different neighborhood search operators at the first phase. Once a solution is found, then the route is fixed for scheduling problem to find optimal departure schedules. If a solution better than the previous solution is found, then it is accepted as the new solution and recorded. If not, we still consider a probability respect to the difference of two solutions to accept the solution. This process is parallel and the best solution could be found. One advantage of our algorithm is the second stage can be easily solved to optimality by existing solver even on very larger instances since it is a linear programming.

Algorithm 1 2-Phase Parallel Variable Large Neighbor Search

Input: - Neighborhood solutions per iteration: κ - Initial solution: S_0

Set current solution $\boldsymbol{S} = S_0$, best solution $\boldsymbol{S} = S_0$, best objective value BestObj $= E_{S_0}$
while $T > T'$ **and** stopping criterion not met **do**
    Reduce temperature $T = \eta T$
    for $k = 1$ to κ **do** ▷ Generate κ neighbors in parallel
        Generate a new solution $\boldsymbol{S'}$ that satisfies constraints
        Optimize departure times for $\boldsymbol{S'}$
        if $E_{\boldsymbol{S'}} < E_{\boldsymbol{S}}$ **then** ▷ Accept better solution
            $\boldsymbol{S} = \boldsymbol{S'}$
        else if Metropolis criterion holds **then**
            Accept $\boldsymbol{S} = \boldsymbol{S'}$ with probability
        end if
        Store objective value $E_{\boldsymbol{S'}}$ in ObjByIter[k]
    end for
    Update $\boldsymbol{S}$ and BestObj if a better solution found among neighbors
    if BestObj not improved for ζ iterations **then**
        Stop search
    end if
    Log iteration info
end while

Output: Best solution $\boldsymbol{S}$ and its objective value BestObj

3 RESULTS AND DISCUSSION

Through simulations and performance evaluations on massive instances, we demonstrate the effectiveness of our approach under different wind conditions, traffic conditions, urban layouts, and number of customers. The multi modal delivery system is shown to potentially improve service feasibility while reducing makespan under multiple uncertainties. Table 1 shows comparisons of expected solutions found under different wind conditions for different delivery systems on 10 runs. We consider the same fleet size but different arrangement to show the capability difference between modes. The customer size and urban layout are the same. With tri-mode system, delivery can be optimally routed and scheduled using less time in total while maintaining low failure rates in 1000 out-of-sample scenarios tests.

Table 1 – *Comparison of different delivery systems with different uncertainties on 20 customers. Results are averaged from 10 runs. T: trucks, D: drones, Tr: tricycles.*

		Tri-mode System (2T-2D-2Tr)		**Truck-Drone (2T-4D)**		**Truck Only (6T)**	
Traffic	**Wind**	Exp. Makespan (min)	Failure Rate (%)	Exp. Makespan (min)	Failure Rate (%)	Exp. Makespan (min)	Failure Rate (%)
Moderate	Moderate	55.4	0	61.8	0	70.5	0
Moderate	Intensive	72.7	5.7	90.0	18.9	73.1	0
Intensive	Moderate	70.1	4.5	81.7	5.2	107.9	10.9
Intensive	Intensive	100.9	10.6	110.8	37.8	115.4	14.8

Under moderate conditions, it records the shortest delivery times with no failures, showcasing its efficiency. Even in intensive traffic and wind scenarios, the tri-mode system maintains better performance, highlighting its robustness against uncertainties. This indicates that utilizing multiple delivery modes enhances service feasibility and reliability while optimizing overall delivery time. We conducted more numerical analysis in full length paper.

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