Last-Mile Delivery Optimization Model with Drones

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Summary: With the increasingly competitive landscape of e-commerce and omni-channel delivery execution, the last mile has emerged as a critical source of opportunity for cost efficiency. Unmanned aerial vehicles (UAVs) have historically been utilized for military applications, but they are quickly gaining traction as a viable option for driving improvements in commercial last-mile operations. We explore the feasibility of deploying drones to the last mile, by modeling the cost of serving customers with one truck and multiple drones in the context of the traveling salesman problem. The model is constructed with mixed integer linear programming (MILP) optimization and assessed by varying several key parameters, such as drone speed and endurance, number of drones available, truck speed, and customer geographic grid area.

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KEY INSIGHTS

1. Across all tested scenarios, the integration of drones in the last mile yields significant cost savings over TSP with truck only.
2. The base case scenario with two available drones – each traveling at 35 mph with an endurance of 30 minutes – yielded a median 30 percent savings over TSP with truck only.
3. In scenarios in which the average truck speed is lowered to 5 mph, we found savings of up to 55 percent over TSP with truck only.

Introduction

Given the vast and growing size of the parcel delivery market, it is crucial for companies to identify pivotal opportunities to gain the competitive edge. The rapid expansion and establishment of e-commerce by companies like Amazon are primary drivers and leading indicators for this growth. In 2015, consumers worldwide spent 1.7 trillion dollars on e-commerce; this amount is projected to double to 3.5 trillion by 2019. To capitalize on this shift, it is important for companies to understand that over half of global parcel delivery costs are primarily incurred in the last mile. This sculpts a developing environment in which the companies that establish the most cost efficient last mile operations will dominate the competition.

Drone delivery as a method to solve for the last mile was first publicly proposed by Jeff Bezos, the CEO and founder of Amazon, in an interview conducted in *60 Minutes*. Amazon was quickly followed by Google and DHL in 2014, Dominoes in 2016, and UPS in 2017. Last mile solutions with drones have since emerged as a front runner in solving for this particular challenge, due to the cost-saving nature of its labor and fuel-efficient design. Although drones face a limited payload capacity relative to trucks and limited flight range, the upside still significantly outweighs the downside. A key advantage offered by drones in this

Truck Variable Costs	
Labor Cost	0.124 $USD/minute$
Fuel Cost	0.418 $USD/minute$
Drone Variable Costs	
Electricity Cost	0.002 $USD/minute$
Drone Fixed Cost	
Deployment Cost	1.136 USD

Table 1. Variable and Fixed Costs

competitive landscape is the speed at which they can navigate through open airspace as opposed to congested traffic on the roads.

Although the benefits of using drones for package delivery appear relatively clear, government regulation has largely lagged behind. Although technically permitted by the US to test, commercial drone operators are required to maintain line-of-sight, operate vehicles under 400 feet above ground level (AGL), register each vehicle, face a limited selection of drone models, and are restricted from flying in many population-based locations. However, recent developments prove optimistic for the US; the White House signed a bill in 2017 overturning the FAA's previous regulation and citing a direction of loosened legislation towards commercial drone operation. Since then, new licenses have been issued by the FAA and the agency is estimating that the number of drone operators will exceed that of private pilots with 450,000 by 2022.

With these recent developments, the integration of drones into last mile delivery is quickly becoming imminent and in need of a robust foundation of research for operational implementation.

Methodology

Key Assumptions:

- Only one truck can be used per tour, while several drones can be dispatched in the same tour. Only one tour is permitted to run at a time.
- Both the truck and drones are set to travel Manhattan distance (Figure 1) instead of Euclidean as a method to emulate movement on road networks to avoid obstacles and prevent private property infringement.
- The drone may only serve one customer node per dispatch, while the truck is not limited in the number of customers it can serve.

Sets:

N	{0,1,…,c+1}: All nodes in problem
N_0	{0,1,…,c}: Nodes that can be departed from
N_+	{1,2,…,c+1}: Nodes that can be arrived to
C	{1,2,…,c}: All customers
D	{1,…,n}: Available drones for deployment

Decision Variables:

x_{ij}	Customer served by truck (Binary)
y_{ijkn}	Customer served by drone (Binary)
z_n	Drone deployed (Binary)

Objective Equation:

$$Min\ Cost = t_{c+1}(C_F + C_L) + \sum_{i\epsilon N_0}\sum_{j\epsilon N}\sum_{k\epsilon N_+}\sum_{n\epsilon D} y_{ijkn}\left(\tau'_{ij} + \tau'_{jk}\right)C_E + \sum_{n\epsilon D} z_n F_D$$

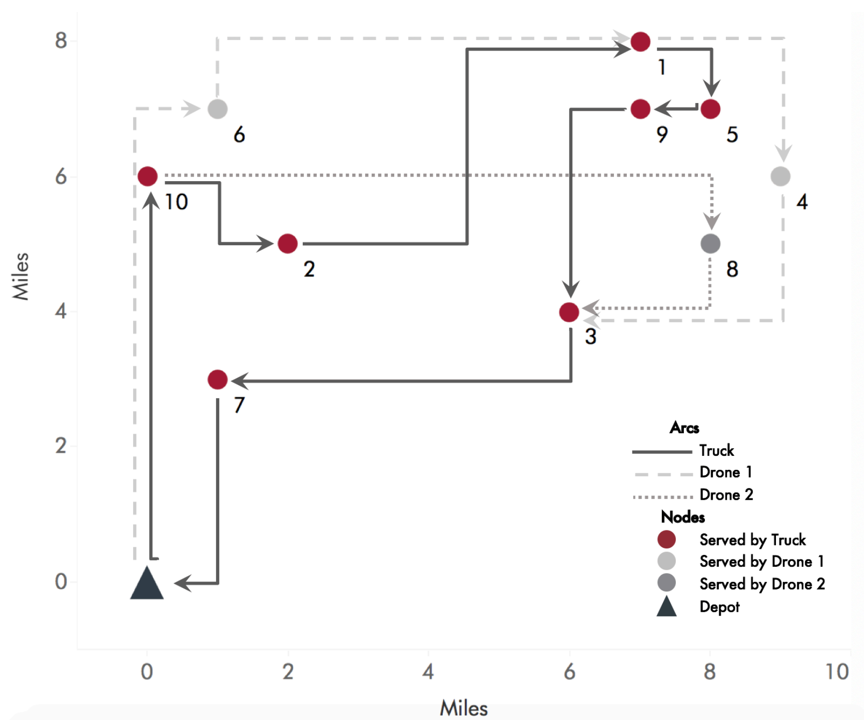

Figure 1. Visual Representation of TSP-MD

The objective function serves to minimize total cost. Total cost consists of the variable cost per minute of truck operation, the variable cost per minute of drone operation, and the fixed costs associated with the number of drones deployed.

Key Constraints:

- Subtour elimination
- Each node visited only once
- Truck and drones coordinate at launch and rendezvous
- Drone flight endurance limit
- Non-negativity constraint

Sensitivity Analysis:

In order to truly understand the effect of drones on last-mile delivery, a wide range of scenarios were explored. Our analysis started with the establishment of the base case, which we determined to be the following: two available drones that travel at an average 35 miles per hour with 30-minute endurance, an average truck speed of 25 miles per hour, and a grid area of 100 square miles. These values were kept constant as each parameter was fluctuated to represent the use cases depicted in Table 2.

Parameter of Interest	available drones D_n	endurance (min_D)	drone speed (mph_D)	truck speed (mph_T)	grid area (A)
Speed/Endurance	2	20 30 40	25 35 45	25	100
Available Drones	1 2 3	30	35	25	100
Truck Speed	2	30	35	5 10 15 20 25	100
Grid Area	2	30	35	25	100 225 400

Table 2. Key Parameters for Sensitivity Analysis

Results

Drone Speed and Endurance:

When varying drone speed and endurance simultaneously, drone speed immediately emerges as the more significant parameter of the two in terms of percent savings gained over TSP. A 10 mile per hour increase from 25 to 35 yields an improvement of over 20 percent in cost savings while an increase in 10 minutes of endurance leads to an improvement in the range of only 2 to 4 percent of average savings as shown in Figure 2.

Although this upward trend driven by drone speed appears to lose its impact when the speed moves from

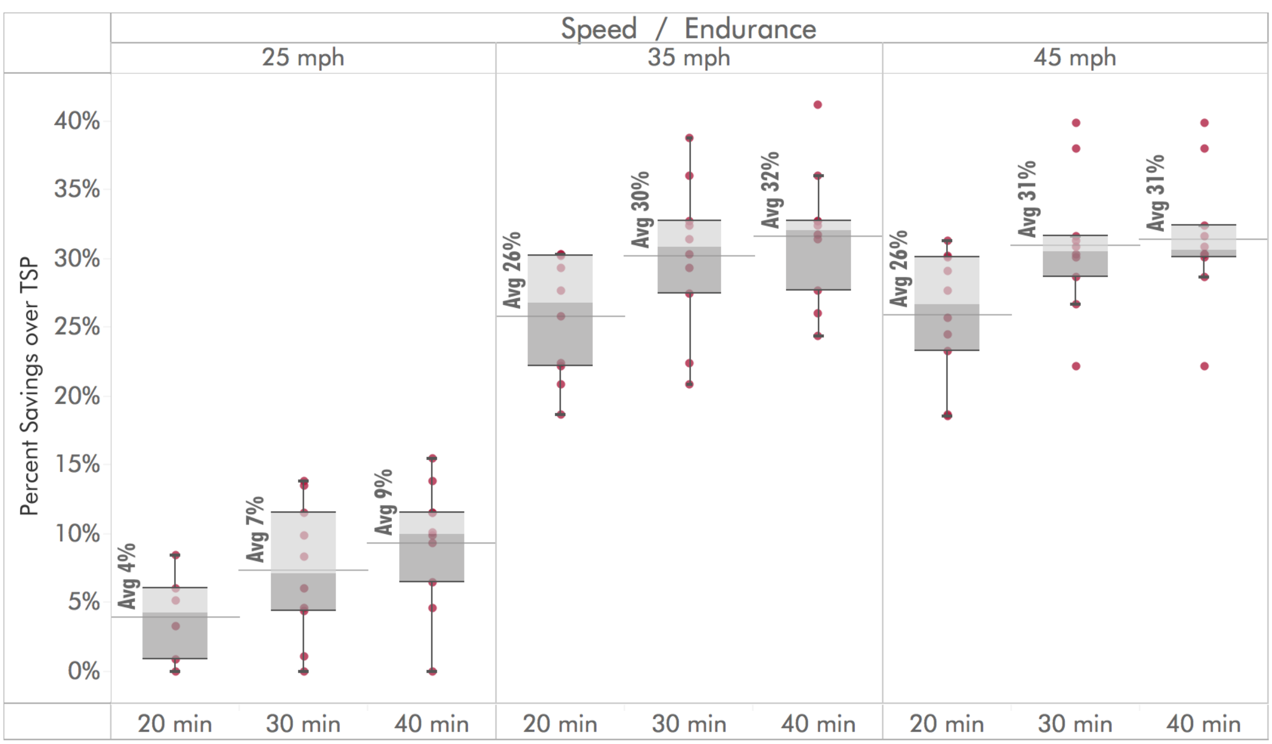

Figure 2. Cost Savings Over TSP Across Drone Speed and Endurance

35 miles per hour to 45, Figure 3 suggests that this is explained by a constraint on the number of drones available for deployment. The maximum number of drones available is reached for all cases at 35 miles per hour drone speed, and this maximum is maintained as the speed moves to 45 miles per hour. While the utilization per drone does increase slightly as depicted as average number of customers served per drone by the line graph in Figure 3, the limit is reached for this metric as well.

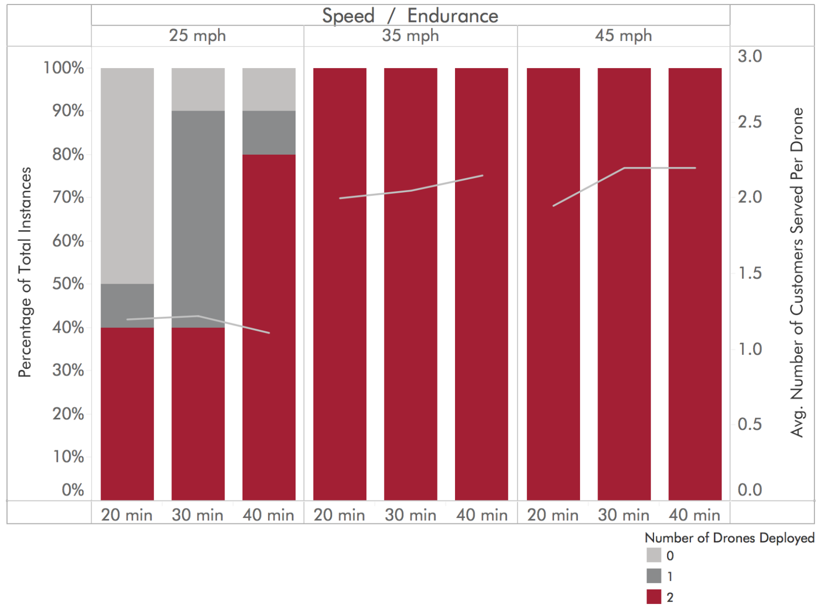

Figure 3. Drone Usage Across Drone Speed and Endurance

Number of Drones Available:

As the number of drones available for deployment is increased, the percent savings over TSP follows the same trend. Increasing availability from 1 drone to 2 drones yields an over 10 percent increase in savings over TSP. However, the relative gain is significantly reduced to only 3 percent as the third drone is introduced into the model.

The model shows a sharp decline in utilization per drone across all scenarios, falling by approximately one customer per deployed drone. However, when the model moved to 3 available drones, there were not enough customers to serve with the newfound capacity. Because there are only 10 customer nodes in the network and 7 serviceable by drones, the three-drone instances were constrained by the lack of density of customers.

Truck Speed:

Cost savings over TSP increases by 10 percent as truck speed moves from 25 to 20, and by approximately 7 percent as truck speed moves from 10 to 5. The savings improvements from the baseline start relatively large and slowly diminish as truck speed is marginally decreased.

Although the number of drones deployed stayed constant at two per instance, the utilization per drone increased steadily as the truck speed decreased. When the average truck speed reaches its minimum of 5 miles per hour, the average number of customers served by each drone reaches its maximum of approximately 3. This observation represents the highest average drone utilization attained throughout the entirety of this study.

Conclusion

Last-mile delivery stands to face significant cost reductions and operational improvements with the integration of drones. Although there are clear use cases that have emerged as an ideal starting point to initiate testing or real-life application with the objective of highest possible gain, all scenarios generated considerable savings over TSP with truck only.

There are several notable topics that would be interesting to explore for the future. One is the trade-off between truck capacity and number of drones available per tour. Another interesting topic is the feasibility of each drone being able to carry more than one package and serve more than one customer at a time.

Regardless of how future research unfolds in terms of exploring the opportunities associated with using drones in the last mile, disruption is imminent. With a recent and rapidly growing demand for better last-mile solutions and technological advancements exceeding commercial applications, very little stands in the way of drone-based delivery becoming a commonality. While our findings show specific use-cases in which drones yield immense cost savings over TSP with truck only, the overall benefits observed across a wide range of residual scenarios are still compelling enough to attract significant investment into research and growth of the field.