Assessing Feasibility of the Delivery Drone

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ABSTRACT

Service level growth is hindered by declining activity from customers needing access to physical assets stored by the sponsor company. The delivery drone presents a viable option to support the initiative of maintaining service levels while reducing cost. To explore the feasibility of the delivery drone, a comprehensive review of delivery drone technology, application, implementation, and regulations is paired with an operational and financial analysis for the sponsor company. The analysis reveals that, given the current landscape, 0% of current deliveries are eligible for drone delivery, but the future potential is as high as 35%. While the delivery drone is capable of maintaining service levels, it has yet to show cost savings potential or practical operational practicality.

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1. Introduction

Drones are a fascinating technology with rich history originating over 170 years ago (Ford, 2018). A drone is simply an unmanned aerial vehicle (also commonly referred to as a UAV) (Karp & Pasztor, 2006). Despite centuries of military development and applications, drones did not exist in commercial application until 2006 (Ford, 2018). While there are various commercial applications for drones, the technology of interest is the delivery drone.

The delivery drone is a UAV that transports goods (“Delivery drone,” 2019). The delivery drone craze started in 2013 when Amazon announced exploration of the field (Ford, 2018). With Amazon’s announcement came a list of challenges and doubts; safety, security, and regulation top the list of concerns (Robillard & Byers, 2013). Despite the skepticism, many industries dove into drone use and found success, particularly in medical and food delivery applications (Rosen, 2017; McFarland, 2018; “Delivery drone,” 2019). With some success, excitement, and a little apprehension, this project analyzes if and when there is a future for delivery drones as part of the sponsor company’s transportation network.

The remainder of Section 1 lays the foundation for understanding the implementation of drones in a transportation network. Many considerations are qualitative. While qualitative considerations do not translate easily into dollar signs, they are important topics for understanding the implications of investing in drones; these subjects are explored in the introduction. After Section 1, assumptions from the qualitative discussion are paired with operational and financial analysis in Section 2 and Section 3. Section 4 is a discussion of all factors considered collectively to answer the sponsor company’s key questions (see Section 1.7 for key questions). Drones may be suitable for delivery in some areas where 15-20% of the sponsor company’s customer network is within the range of current technology.

1.1 Motivation for exploring drone delivery

Many executives are speculating whether drone delivery can replace truck and van transportation. Amazon, Boeing, UPS, FedEX, and DHL are just a few of the major competitors working with delivery drones (“Amazon.com,” n.d.; Davies, 2018; McFarland, 2017; “Delivery drone,” 2019). While not explored in this assessment, consumer preference and interest are another motivation. Drones may provide the capability to reach customers faster, more efficiently, and perhaps most important, potentially at lower cost than traditional automotive delivery networks.

1.2 Drone Technology Today and Tomorrow

Drones are making the news in both positive and negative ways. In some cases, drones are making positive changes, providing lifesaving medical equipment to remote areas; however, there are also stories of unwanted surveillance and midair collisions with piloted aircraft ("Boeing 737 Passenger Jet Damaged in Possible Midair Drone Hit," 2018; Rosen, 2017). While the media provides some coverage regarding drones in supply chain, it is important to look more deeply to assess the current and future potential of drones.

When considering drones suitable for delivery, the 55 pound (~25 kilogram) limitation currently imposed on drones and their cargo is required to be compliant with US FAA regulations ("Fact Sheet – Small Unmanned Aircraft Regulations (Part 107)," n.d.). Figure 1 gives a brief comparison of some of the current technology that may be adaptable to drone delivery.

Most drone technology runs off battery technology, but some drones on the market like the Airborg H8 10K run off of a hybrid powerplant ("New Airborg H8 10K - Top Flight Technologies," n.d.). Battery operated platforms meet minimum performance specifications, but hybrid platforms like the Airborg offer increased range, payload, and speed. The increased performance also comes with a need for additional labor, fossil fuel, and weight. The labor creates a burden that softens the incentive for drone delivery savings. The fuel eliminates the prospect of sustainable technology, which is a desired feature of delivery drones. The additional weight of some designs like the Airborg model require lobbyists to campaign for additional weight allowance in regulations. While some limitations exist for battery technology, it is a chosen assumption for the analysis in Section 2 and 3. Benefits such as performance are not neglected here, but the project seeks solutions of longer-term considerations.

Product	Payload	Cruise Speed	Endurance	Weight
 Airborg H8 10K[1]	4 kg (8.82 lbs) 10 kg (22.04 lbs)	55 kph (~34 mph)	2+ hour 1+ hour	33 kg (~73 lbs)
 Flytrex Sky[2]	0.75 kg (1.65 lbs)	36 kph (~22 mph)	30 minutes	1.25 kg (~3 lbs)
 Prime Air[3]	2.26 kg (5 lbs)	80.5 kph (50 mph)	30 minutes	25 kg (55 lbs)

Figure 1: Delivery Drone Specifications

The goal for a delivery drone is an ideal balance of payload, speed, endurance, and range. Given weight and sustainability constraints, finding a delivery drone that has optimal performance characteristics is challenging. While the weight and sustainability constraints are likely to stay consistent, performance specifications will increase capabilities in the coming years. Predicting how drastically these characteristics will improve presents a challenge as research and development is limited to primarily large companies, which do not share information. Given the technology today, the project assumes the performance characteristics in Table 1.

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[1] http://www.tflighttech.com/products/media-airborg-h8-10k.html
[2] http://x.flytrex.com/support/flytrex-sky/tech-specs/
[3] https://newatlas.com/amazon-new-delivery-drones-us-faa-approval/36957/

Table 1: Delivery Drone Specifications Derived from Current Technology

Maximum payload	5 lbs
Maximum range	35 mi
Average speed	35 mph
Endurance	1 hr

Speed, endurance, distance, and payload are critical benchmarks in drone technology to determine their relevance in supply chain enhancement. Amazon and UPS are paving the way in technology with reported speeds up to 100 miles per hour, 5 pound payload, and delivery time less than 30 minutes based on a maximum distance of 10 miles between the consumer and fulfillment center (Desjardins, 2018). Top Flight Technologies has a hybrid-powered drone, Airborg™ H8 10K, available with more robust payload capability at 10 kilograms for 1 hour or 4 kilograms for 2 hours. Additionally, the drone is capable of withstanding wind gusts up to 35 miles per hour and flies at a speed of 40 miles per hour with a range of 100 miles ("New Airborg H8 10K - Top Flight Technologies," n.d.).

A couple other topics of interest for current and future delivery drones are how they will interact with customers and company employees. While public opinion and perception of drones is not considered in this project, drone interaction with customers is an important criterion when assessing the feasibility of commercial drone delivery. Amazon holds a patent for drones that respond to human gestures (Shaban, 2018). Other sophisticated technology uses boxes the drone can fly into for safe recovery and recharging ("H3dynamics," 2016). While these specific technologies are not critical to gauging the feasibility of drone delivery, they serve as important benchmarks to ensure feasible economic solutions are available to make deliveries.

1.3 What industry has done

Drones are making deliveries in exciting ways: one golf course uses drone technology to deliver golfers food on the course by lowering it down to them from a safe flight altitude (McFarland, 2018). Drones are popular in the medical industry for delivering time critical supplies to remote areas (Rosen, 2017). Given drones are trusted with lifesaving equipment, it is reasonable to claim that technology will continue to improve in security and reliability to meet the demands of any application. The research by Amazon and UPS proves the capability of drone technology to be a viable source for delivery in the near future (Desjardins, 2018; “Amazon.com,” n.d.). While challenges will occur with drones making deliveries, current research and applications are sufficient to assume the potential for future applications.

The leaders in delivery drone research, development, and implementation are Flytrex, Flirtey, and Prime Air. Zipline is also successful, but they have focused their attention on medical supply delivery in developing countries. Flytrex is successful with small operations like the aforementioned golf course employment. Flirtey is working with Dominos et. al. on projects. Prime Air is not making many announcements about their progress, but they advertise a successful delivery in the UK from 2016? While the manufacturers are likely to change with drone delivery progress, Flirtey and Flytrex seem to be the most reasonable companies to work with presently (“Top 100 Drone Companies to Watch in 2019,” n.d.).

1.4 Challenges with drone delivery

1.4.1 Weather

The weather forecast plays a significant role in drone operations. One of the more significant issues with drone technology is restricted use during foul weather. Foul weather is used as an intentionally ambiguous term. Performance characteristics are important to consider in current and future technology to determine whether drone flight is suitable. Four primary considerations for weather are wind, visibility, precipitation, and temperature.

Currently, the most significant limitation is wind. Wind speeds and gusts are challenging limitations for drones. Some larger model drones, like the Airborg H8 10K, are capable of flight with wind speeds and gusts up to 35 mph (~55 kph). It is unlikely that a drone in compliance with the 55 lbs (~25 kg) weight constraint in US FAA flight regulations would be capable of performing in winds at that speed or higher. Many geographic areas have significant challenges with wind speed. From wind gusts in urban environments to coastal wind effects, some locations are not well suited for routine drone operations.

Another limitation for drones is visibility. While fully autonomous drone technology is readily available, US regulations still mandate the drone must be kept in sight by an operator at all times ("Fact Sheet – Small Unmanned Aircraft Regulations (Part 107)," n.d.). Visibility may not be a long-term weather consideration for drone delivery, but given current regulation constraints, visibility conditions below the 400-foot maximum altitude above ground level for drones would be a significant limiting factor.

Other forms of adverse weather are also a threat. It is unwise (and in some cases infeasible) to fly in cases where there is significant precipitation. While flight may be possible, many drone models are not suited for prolonged exposure to wet conditions. Flying in such conditions would come with degraded performance, extra maintenance, and potentially other adverse effects from corrosion or electrical issues. Many models are built with minimal protection to help reduce weight and enhance aerodynamics.

The last consideration for drones regarding weather is temperature. This issue is two-fold as it presents potential issues for cargo and the drone itself. With current technology, drones are not well suited for temperature sensitive cargo. The weight associated with insulated cargo space is often bulky or heavy. The drone itself faces potential issues in extremely warm or cold climates. Motor, aerodynamic, and battery performance are a few limitations delivery drones encounter is extreme temperatures. Flight performance is degraded in hot and humid conditions. For drones potentially operating near maximum performance for payload, hot climates may not be permissible for flight. Freezing conditions present other challenges. Drones are not well equipped to encounter icing; cold climates (and potentially seasonally for many climates) are not a good candidate for drone technology. Lithium-ion batteries do not perform well in temperatures below freezing or above approximately 100°F (~40°C) (Wang et al., 2016).

With all of the different effects weather can have on drone operations, the focus of this study is on climates where fair conditions are likely guaranteed. This does not eliminate the concerns regarding weather, but it shifts the focus to other important considerations in the process. Given a favorable outlook for other aspects of drone delivery, weather would be a strong last determining factor on whether drone delivery is feasible.

A company with a drone delivery network needs significant planning in place to maintain business on bad weather days. Unlike commercial airlines that perform steadily in foul weather, drones are likely unable to fly on foul weather days. As an aside, this problem will likely exist for some time since the best way to solve this issue is with larger, more capable drones. On days where drones are grounded, a need for an alternate delivery plan or a flexible customer network exist. Since the latter is likely not reality, operations executives face a challenge of balancing the use of third-party logistics, a backup truck and van network, or an overtime policy for delivery vehicles and drivers. These adjustments may come at a high premium, especially for instances with a large and/or frequently used drone delivery network. Coupled with that challenge, determining the appropriate time to call off drone operations due to weather is a costly endeavor. Making the wrong call well ahead of time comes at a cost. Making the right call too late comes at an even higher cost. Optimizing solutions and business models with these problems would take significant time and money.

The weather is a powerful influence on drone delivery. Studying the impact of weather on operations is a critical component of using drones as a cost-effective delivery alternative.

1.4.2 Regulations

Regulations are a crucial consideration for drone delivery. Becoming a stakeholder in delivery drones comes with a future in lobbying. While there are different rules and regulations around the world, this research centers on the United States. The Federal Aviation Administration (FAA) is the United States' authority on aviation regulations. Most of the challenges discussed are negative and presented as problems. They are not impossible to solve, but all of the issues require research, dedication, and communication.

The biggest hurdle with regulations is the current line of sight (LOS) stipulation. The regulation requires the drone to be in visual site of a remote pilot certificate holder with a small UAS rating at all times. All solutions enabling line of sight cost money due to the cost of drone pilots and required visual observers. The latter cost inhibitor raises the problem of how to maintain LOS. Various observation towers or transporting operators via vehicle may be a solution, but these solutions are not practical for a service that intends to reduce labor and carbon emissions for a company.

Another issue is the use of airspace, particularly around airports. Operating a drone in class B, C, D, and E airspace (usually encountered near air traffic control towers, see Appendix A for background information) requires permission, planning, and coordination. Existing infrastructure for air traffic controllers to potentially maintain sight and some control of drones is available. Solving the problem takes coordination between drone operators, local airport authorities, and the FAA. This challenge is not being discussed and is likely to take a significant amount of time to implement and control.

The Federal Aviation Administration has dictated drones may not fly over humans, be operated from a moving vehicle (except sparsely populated areas), or the operate outside of daylight ("Fact Sheet – Small Unmanned Aircraft Regulations (Part 107)," n.d.).

Maximum speed and altitude are likely not critical concerns as 400 feet above ground level and 100 miles per hour are near the limits of current small drone performance. The weight limit for small drone operation in 55 pounds. Payload of less than 5 pounds is likely in order to meet the current weight limitations.

Regulations are considered in the project, but they are not considered to the full extent. It is likely the regulations will be amended and/or change over time once some of the challenges are solved. In fact, 2019 has shown remarkable progress for waivers to these regulations. For the last several years, waivers have been limited to primarily requests to operate at nighttime. Recently, waivers have been granted for most of the restrictions above; however, additional constraints are often associated with the waivers ("Part 107 Waivers Issued," n.d.).

1.4.3 Additional operational considerations

Finding suitable cargo containers to move goods with a delivery drone presents some challenges. The ideal container is aerodynamic, light weight, durable, secure, and suitable for many different items. The container needs some sort of security mechanism and can ideally withstand abuse from a crash or criminal activity. These considerations provide incentive for minimizing the number of containers to avoid the high cost of design and inventory. For the sake of this project, a solution that can handle 1.2 cubic feet of cargo is used. Sufficient tracking, durability, airworthiness, and other applicable constraints are assumed. Like the sponsor company's current business model, the containers could be returned by the van and truck fleet that continue to serve the customer.

To meet safety and security regulations, a technology such as a transponder enabled kill button may prove effective for drones. This provides the operating company or regulatory agency a means to prevent the drone from creating an unsafe situation.

It is also interesting to consider what types of airspace agreements could be made to accommodate drone traffic. Regulations are currently very restrictive, but constraints similar to rules for helicopters would enable many more possibilities for drone technology. Experts in aviation are a requirement for establishing drone services for a company. These individuals would establish flight paths and coordinate agreements on where and when drones could operate within the airspace system with the FAA and local airspace officials.

Some geographic areas are not hindered as significantly by current regulations as others. Areas with a significant amount of water sources provide safe flight paths that avoid overflight of populated locations. Regardless of the local geography, having personnel to lobby for reasonable weight allowances and exceptions is an important component of a drone delivery business strategy.

Drone network routing for the analysis in this project considers trips directly to a customer from a sponsor company facility. Matternet is partnered with Mercedes Benz on deploying drones from specially adapted vans (see Appendix B for more information on Matternet). This technology allows drones to deliver faster service for priority orders, which could provide substantial value to the sponsor company's operations. UPS is also exploring this approach and has partnered with Matternet. With current technology, the designs and planning to employ this technology are limited.

1.4.4 Aviation realities

Maintenance and inspections are time-intensive and costly. Currently, the FAA does not require airworthiness certifications for small drones, but they might in the future. This coupled with drone registrations presents opportunity for cost increases in the future. The responsibility of preflight inspections lies with the operator of the drone. This would likely come with a bit of a learning curve to figure out what to inspect and when. Some drones have self-diagnostic software to check for equipment degradation, but there are additional costs for such technology and a need for maintenance personnel to correct issues as they arise.

1.4.5 Insurance

While it is feasible to assume the probability of accidents compared to truck and van delivery options would not increase, the severity is potentially higher for aircraft collisions or crashes. Consideration and planning would be needed for how to deal with lost documents. For the sake of our financial analysis we consider that insurance costs for drone delivery would be equal to the amount for traditional delivery systems.

1.4.6 Autonomous versus human operated

It would be extremely difficult to justify drone operations using pilots instead of autonomous operations. The savings in labor is the biggest impact of drone implementation to supply chain. For the sake of our analysis, we consider autonomous operations, which is not currently legal in the United States. Companies like Amazon have already conducted autonomous drone flights, but they require waivers and follow on restrictions to operate ("Amazon.com," n.d.; "Part 107 Waivers Issued," n.d.).

1.5 Scope

While the drone industry has been active for the last decade, substantial advancement in technology and regulation is ongoing. This assessment of drone delivery will examine current technologies and provide insight on the cost feasibility for current and future drone delivery implementation. Our study is limited to sponsor company operations in the United States based on one year of data from 2017.

1.6 Methodology

Regions with high customer volume and favorable weather conditions for drone operations are the focus of this assessment. San Diego, Los Angeles, San Francisco, Houston, and Dallas are selected as possible locations to study current and future applications for drone operations.

1.7 Research Questions

The sponsor company desires to know if drones may be a viable option to include in the optimal vehicle fleet composition. If so, they desire a timeline of when the implementation could occur. Finally, the company requests a recommendation of the percent of deliveries eligible for drone delivery based on regulatory, operational, and financial considerations.

2. Methodology

Operational and financial analysis was conducted after carefully considering all of the factors of implementing a delivery drone network. The drones examined in this research are near or completely in compliance with current US FAA regulations in regard to performance; however, it is assumed the drones could operate autonomously without human operators flying them. Many waivers have occurred recently (early 2019) to relax this requirement, but the analysis relies on this assumption to provide a realistic cost assessment. Given the technology supports autonomous drone operations, other researchers have taken the same approach in regards to cost analysis as well ("Part 107 Waivers Issued," n.d.; Jenkins, Vasigh, Oster, & Larsen, 2017). In addition to autonomous flight, weather was a strong influence on how drones could operationally perform. To avoid tunnel vision on challenges with weather, the analysis chose locations where there are ideal weather conditions for aviation. Consideration was also given to locations where the sponsor company has significant volume. The locations considered are San Diego, Los Angeles, San Francisco, Dallas, and Houston.

2.1 Operational Feasibility Study

Operational feasibility was defined by 2018 data from the sponsor company. Approximately 30-50% of the data had all of the relevant fields for analysis. Although there were potential limitations to the data, sufficient information to perform the analysis was available. No scaling or data manipulation was done to speculate missing entries. Cases where critical data was absent in a record, namely missing locations or fields required to link deliveries to specific routes, were excluded from the analysis. Data for airports was taken from the Federal Aviation Administration and manipulated in Tableau and Excel.

2.1.1 Understand Regulatory Landscape for Drone Delivery

The first part of operational feasibility was a qualitative analysis of current regulations. Regulations have relaxed with time and lobbying efforts. Although not currently legal, autonomous operations are assumed feasible in the analysis. Depending on the length of time this restriction holds, drone delivery will likely stall as the challenges of training and using drone pilots and visual observers present a significant challenge in both logistics and cost.

2.1.2 Define Feasible Metrics for Drone Delivery

Drones can be deployed and routed to deliver to a customer network in a variety of ways. All routing in the analysis assumes direct trips from business to consumer to business.[4] The restrictive metric for this stipulation is range. Range was defined as the distance a drone can travel considering all phases of flight: takeoff, transit, and landing. Radius was the distance between the sourcing sponsor facility and the customer. Current technology provided a feasible delivery radius of 17.5 miles (28 kilometers) for a range of 35 miles (56 kilometers). The analysis tool was designed to adjust for both sensitivity analysis and adjustments for different models of delivery drones (see Appendix D for screen shots of the analysis tool).

Payload was defined as the weight of the cargo the delivery drone carries. Payload considered current technology, regulations (i.e. the 55-pound FAA limit on drones), and data from the sponsor company ("Fact Sheet – Small Unmanned Aircraft Regulations (Part 107)," n.d.). The individual cargo data from the sponsor company was in cubic feet. The first assumption was to filter out all deliveries with cargo exceeding 1.2 cubic feet. This metric was examined to give future insight assuming a drone could handle all deliveries less than or equal to 1.2 cubic feet. To account for current and future technology limitations, the weight distribution in Table 2 provided by the sponsor company was used to determine how many of the 1.2 cubic feet packages were eligible for drone delivery. 5 pounds was used for current technology, and the future was analyzed with 10 pounds, 15 pounds, and 20 pounds considered as pessimistic, likely, and optimistic 5-year forecasted payload limitations respectively.

Table 2: Sponsor Company Weight Distribution for 1.2 Cubic Feet Containers

Pounds	Percent
5	3%
10	10%
15	20%
20	30%
25	20%

[4] Appendix C references some of the research being conducted on drone networks at MIT.

30	10%
35	5%
40	2%

Speed was considered as an average based on current technology and regulations (maximum allowable speed for a drone is 100 miles per hour) ("Fact Sheet – Small Unmanned Aircraft Regulations (Part 107)," n.d.). Speed for the analysis is 35 miles per hour (~56 kilometers per hour). Speed was not used in the project analysis, but it is an important contributor to follow on analysis calculating the time required to perform a delivery to the customer.

Endurance was the amount of operational time a drone could fly without recharging. Our analysis considered the endurance qualitatively as a single trip to a customer followed by 30 minutes to 1 hour of charging based on the distance flown. Like speed, endurance was not part of the analysis, but it was an important consideration for operational analysis.

Airport proximity was considered to understand potential delivery network challenges. The closer a customer or company facility is to an airport, the more difficult it would be for drones to operate in the area. There are ways around some of these challenges, but agreements with local airports, the FAA, and flight routing would require significant effort. Airport proximity was measured as the distance between the customer and the center of an airport. The airport proximity was 6 miles (~10 kilometers) for the analysis.

The sponsor data included information about priority and rush deliveries. The analysis did not filter out any of the deliveries based on these criteria; however, the analysis tool enabled further exploration of removing certain priority or high security deliveries for future consideration.

Given these metrics, we assessed the percentage of deliveries eligible for drone delivery. The metrics were adjustable to reassess based on technology improvements, regulation changes, airspace agreements, and other related factors. The analysis tool provides the capability of adjusting all of the parameters to adjust for improvements in technology, changes in regulations, and business preferences (i.e. security, priority). Each of the metrics was assessed both independently and collectively. The collective assessment considered range, payload, proximity, and business preferences respectively.

2.1.3 Operational Sensitivity Analysis

Once the operational analysis was completed, sensitivity analysis was performed to identify critical points in the metrics. This was performed with the analysis tool by adjusting the metrics considered in the operational feasibility.

2.2 Financial Feasibility Study

2.2.1 Establish Baseline Model

The sponsor company currently leases their vehicle fleet. The baseline model assumes the vehicle fleet is upheld; the savings in the model came from fewer miles and less manpower. The three existing transportation costs include fuel, maintenance, and driver cost.

Fuel cost was variable by location and was volatile for future predictions; however, the implementation strategy for the analysis performed was relatively insensitive to fuel. Given a variety of selected sponsor company locations primarily in California and Texas, a fuel price of $3.50/gallon ($0.92/liter) was selected.

Maintenance cost for drones was liable for fixed and variable costs per mile. Some research exists on this subject, but the analysis for this project arrived on a cost of $0.10 per mile.

Driver cost was considered at $20/hour. There are potentially unexplored cost savings on drone deliveries cutting back on overtime that remain unexplored.

Investment costs include drone cost, container cost, and infrastructure cost.

Drone cost is highly volatile and not easy to estimate. Given current technology, $10,000 was a comfortable estimate for a delivery drone.

The current containers used by the sponsor company would not be sufficient for drones, so an investment in containers was also a necessary expense to consider. Given assumptions about current usage of cargo containers, an estimated 3:1 container to delivery drone ratio was used to determine the number of containers. Container cost for a secure and safe container was estimated at $100 per unit.

Infrastructure costs would be minimal for the proposed solution of sponsor facility to customer to sponsor facility. A more reasonable solution like the Matternet and Mercedes model of flight from business to van to business would require significantly higher infrastructure costs for vans capable of receiving delivery drones. A simple $10,000 per facility for drone operations was considered. The cost would cover partitioning an area suitable for drone takeoff and landing. IT upgrades and other implementation costs were considered separately at $40,000 each. This would cover required software, hardware, and administrative resources. Again, the costs are estimated; Flirtey, Flytrex, Top Flight Technologies, and Matternet were not responsive to academic inquires on costing.

Fuel, driver costs, and vehicle maintenance costs are three costs where drone delivery can create savings. Battery-powered drones were considered exclusively in the analysis, so fuel cost represented a direct savings for every mile covered by drones. Appendix E provides further insight on how the miles saved were calculated.

Driver's wages were calculated by a function of an hourly wage, how many miles were saved by drone usage, and an average speed including stops of 25 miles per hour (~40 kilometers per hour).

Maintenance was liable for fixed and variable costs per mile. Vans and trucks had different costs, but they were collectively combined into one metric of $0.20 per mile.

All of the costs above were used collectively to calculate the net present value (NPV) based on the results from the operational analysis (further detail on the calculations in Appendix E).

2.2.2 Sensitivity Analysis

Factors displaying a significant impact on NPV were analyzed by applying a 50% increase and decrease on each of the costs. The significant cost drivers included: salary for drone specialist, drivers' wages, total investment cost, drone cost per unit, gas price, and drone operating cost. A 50% delta was applied to each individual cost to show total impact on NPV.

2.2.3 Incorporating flexibility by considering timing options (now or later)

Given the key metrics assessed in the operational and financial analysis, the model predicted three different 5-year forecasts for a likely, pessimistic, and optimistic outlook. Each of the variables were manipulated collectively to provide a range of NPVs for each city assessed in the project. The intent of this analysis was to provide guidance on whether investment in the near term or the future were potentially beneficial for implementing a delivery drone solution into the sponsor company's transportation network. Additionally, a $20 surcharge for all drones was implemented for an independent analysis to show the merits of using drones as a value driving investment in parallel with cost saving metrics.

2.3 Conclusion

The analysis conducted was designed to give a comparison of vans and trucks versus drones. The analysis gives a high-level overview of cost comparisons on the portion of deliveries that could be handled by drones without any extensive delivery network modifications. Given the current balance of drone technology and the customer network of the sponsor company, the van and truck network are still an essential component of the transportation fleet.

A number of opportunities exist for revisiting the analysis. When the division of labor for delivery drone tasks is better known, a more extensive cost comparison could be made. Significant advances in drone technology could also be an incentive to research drone applications further. Given the number of waivers being granted by the FAA and assumptions made in the analysis, changes in regulations are rather insignificant to the analysis. The line of sight stipulation is a significant inhibitor to the technology; the analysis ignored this requirement as the whole operation would not be feasible with it.

Many details that are significant in cost are not captured in the analysis. Future research may factor in the cost of cellular network access plans for drones. These costs were absorbed into a conservative cost per mile figure for the assessment, but a more thorough understanding of cost impacts would be required in future analysis. The factors considered give a conservative look at expenses that would be encountered; however, experience in commercial aviation presents a fair opportunity for cost overruns whether it be from insurance, unpredicted maintenance, or unexpected labor requirements. See Appendix D for visualization of the analysis tools.

3. Results

San Diego, Los Angeles, San Francisco, Houston, and Dallas were analyzed for their favorable weather conditions for drone operations and customer volume of the sponsor company. Operational results are presented first followed by financial analysis performed using results derived from the operational analysis.

3.1 Operational Analysis

Each city is summarized with a wedding cake model. The base layer represents every record delivered in each respective city for calendar year 2018. The next layer, drone flight distance limitation, is set to a distance of 17.5 miles (~28 kilometers). The percentage represents how many of the total deliveries are less than 17.5 miles from the sponsor facility from which they originated. Drone payload was set for 1.2 cubic feet for initial analysis, but it was later constrained by a weight distribution provided by the sponsor company for 1.2 cubic feet containers. Airport proximity was set to six miles. This layer filters out all customers within 6 miles (~10 kilometers) of sponsor company facilities. The top layer is a filter for priority and confidentiality; the model was set not to constrain the deliveries by this metric. The model has the capability of showing how each individual constraint affects the total deliveries for the city;

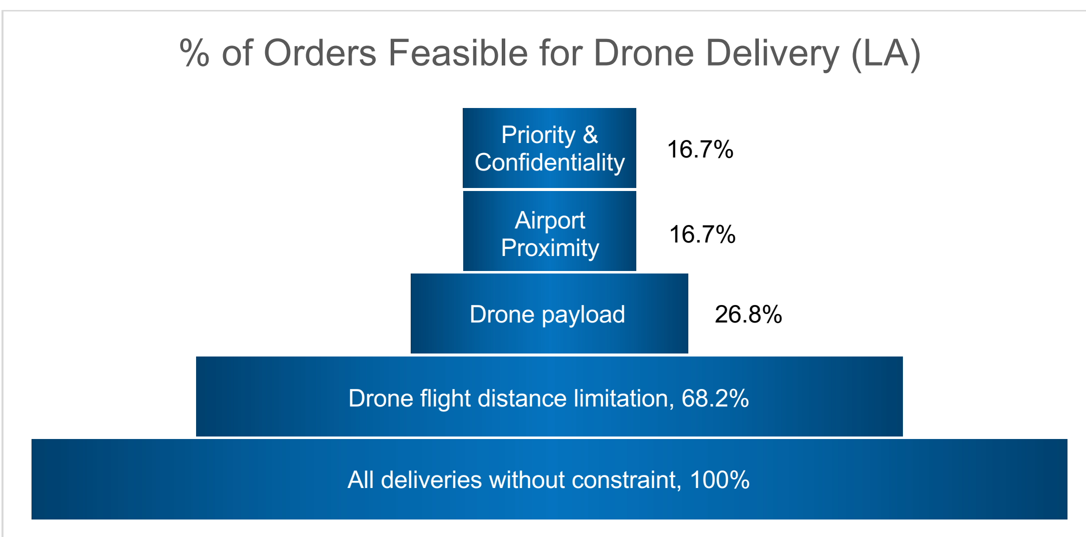

Figure 2: Operational Feasibility of the Delivery Drone for Los Angeles, California (All 1.2 cubic feet or less cargo)

however, Figures 2 (see Appendix F for other cities) show the cumulative effect of each constraint applied in order from the bottom up.

Since weight distribution for 1.2 cubic feet containers was available, Figure 3 and Figure 4 below show the difference in the operational constraints with a 5-pound and 20-pound limitation. These constraints are used later for a current and 5-year optimistic forecast for delivery drone payload capabilities. All of the researched cities had similar results in the 0.2%-0.6% range for the 5-pound limitation. Appendix F shows an additional version of Figure 3 and Figure 4 for San Diego; San Diego has the most promise for future feasibility based on payload capabilities. While airport proximity is minimized considering payload first, keeping the filters in order is important as airport proximity could be more likely mitigated than payload constraints.

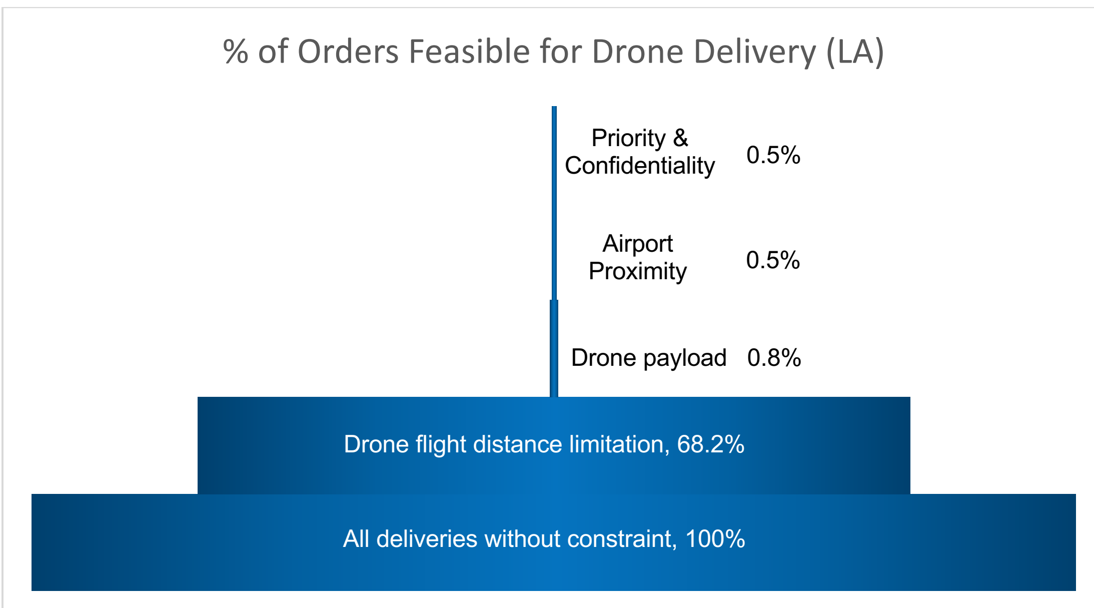

Figure 3: Operational Feasibility Adjusted for Average Weight Distribution of 1.2 Cubic Feet or less Cargo ≤ 5 pounds

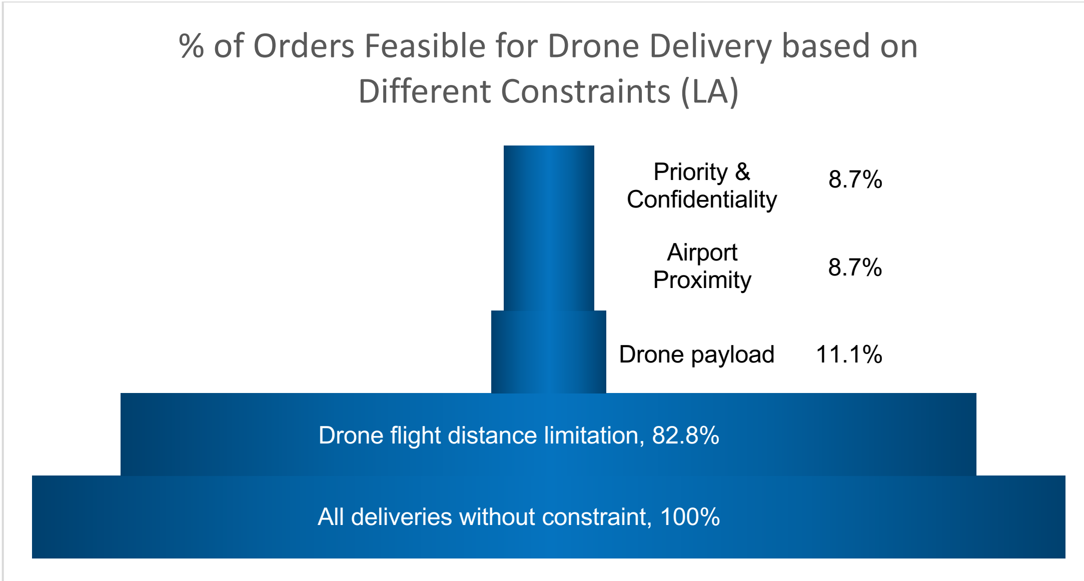

Figure 4: Operational Feasibility Adjusted for Average Weight Distribution of 1.2 Cubic Feet or less Cargo ≤ 20 pounds

3.2 Operational Sensitivity Analysis

Sensitivity analysis was performed for the layers of the operational model.

To determine the maximum distance between the customer and the sponsor facility, it is important to assess both slightly above and below the 17.5-mile (~28 kilometer) distance used in the assessment above. Some drone models are incapable of servicing the 17.5-mile range with their current battery technology and weight restrictions. On the other hand, a longer range is possible as drone technology improves and flight range and endurance increase. Figure 5 (see Appendix F for other cities) shows the maximum flight distance sensitivity for the cities researched. An example of a significant jump in the results can be seen in Los Angeles. A delivery drone range of 26.5 miles services approximately 83% of deliveries, but 27 miles services about 95% of deliveries.

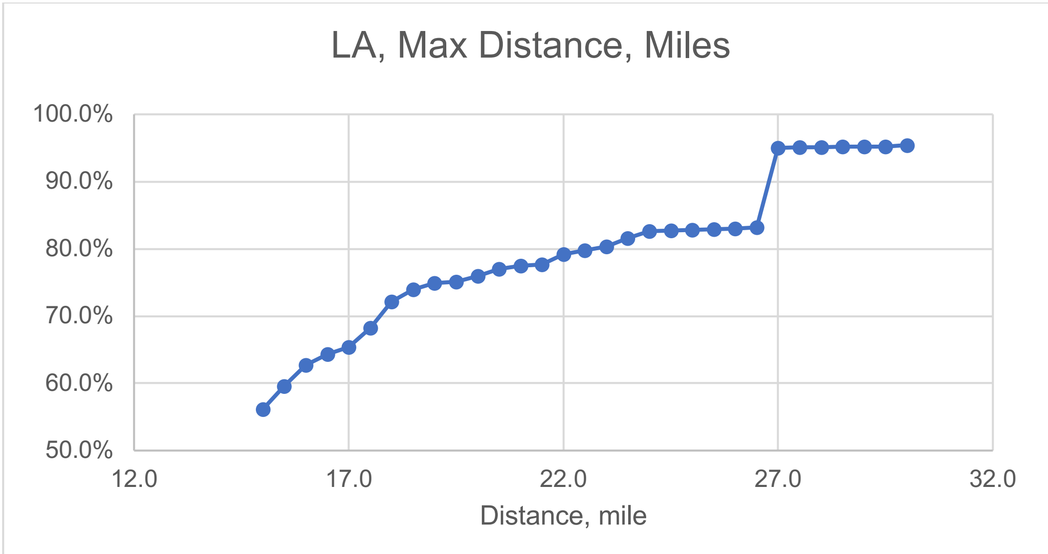

Figure 5: Max Flight Distance Sensitivity Analysis for Los Angeles, California

Payload is one of the more important considerations to make when assessing operational feasibility. The data from the sponsor company came in 1.2 cubic feet increments for the majority of the data. For further exploration of payload analysis, weight is more critical to examine than volume. Sensitivity analysis was performed for volume with sponsor data. Sensitivity analysis by volume in Figure 6 (see Appendix F for other cities) is a valuable analysis that shows the high volume of 1.2 cubic feet containers. In most cities, the payload capacity improvement beyond 1.2 cubic feet is not significant,

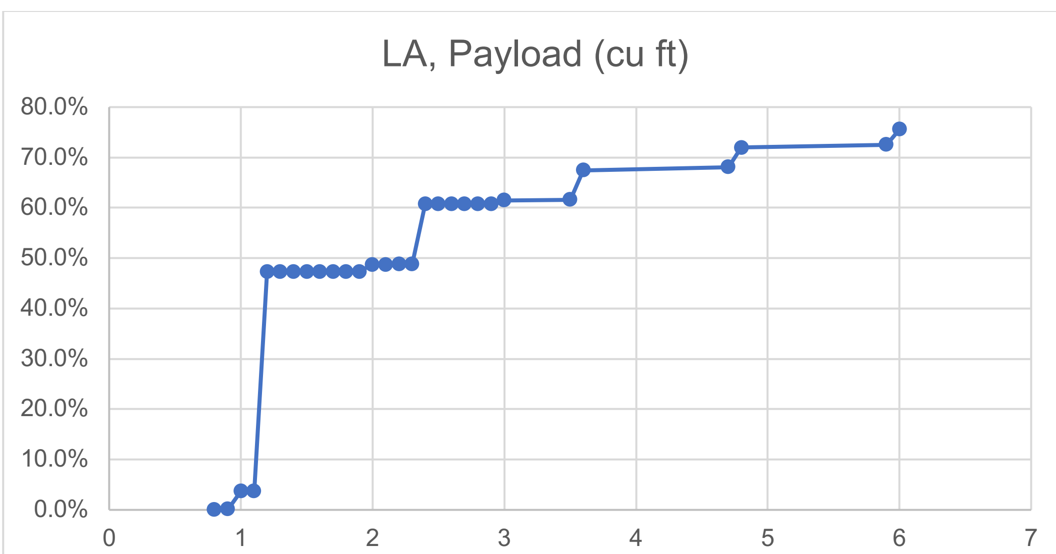

Figure 6: Payload Sensitivity Analysis for Los Angeles, California

but Los Angles shows a good example of a greater than 10% increase in eligible deliveries for double the payload capacity.

The importance of customer locations to airports is a slightly more subjective constraint. In some areas, close proximity to an airport may be a bigger challenge than others. The analysis used a 6-mile (~10 kilometer) distance, meaning the customer is within 6 miles of a major airport with Class B, C, or D airspace. The challenges of regulations and operations would become exponentially more complicated with each mile closer. Figure 7 (see Appendix F for other cities) shows what percentage of customers are outside the given number of miles. For example, in San Diego about 88% of customers are at least 3 miles from an airport, but only 36% are 3.5 miles away. In this instance, 3 miles would be a significant radius to lobby for to expand the percentage or decrease the complexity of eligible drone deliveries.

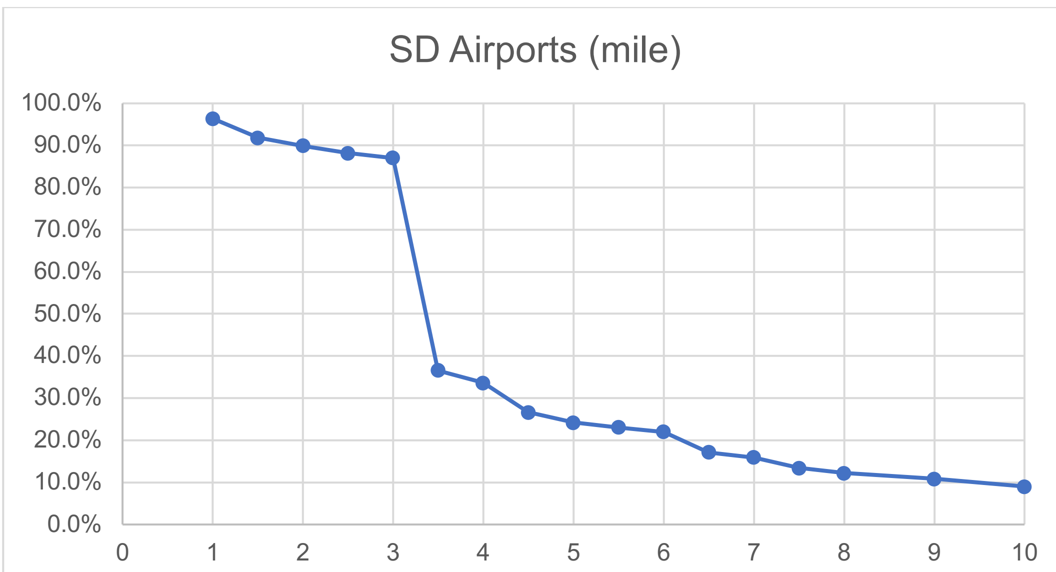

Figure 7: Percentage of Customers greater than X miles from a major airport in San Diego, California

3.2 Financial Analysis

3.3 Financial Sensitivity Analysis

Wages for drone specialists were the most significant impact on the financial analysis. The personnel costs for drone specialists was nearly matched with the overall net present value change. For instance, Los Angeles shows a 62% increase or decrease in NPV with a 50% decrease or increase in drone specialist costs respectively. Other locations showed an even more significant impact for drone delivery specialist salaries (see Appendix F); San Francisco was the highest with a 100% change in NPV for a 50% increase or decrease in drone specialist salaries.

Los Angeles showed the general trend for cost impacts, although the order of other cost drivers was not conclusive for the five cities in the research.

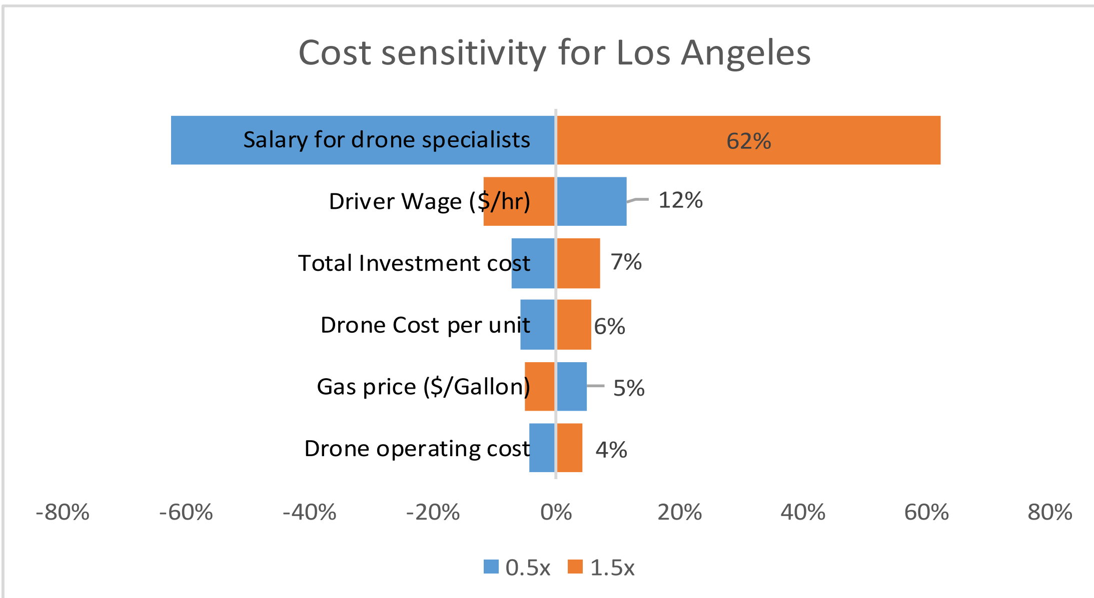

Figure 8: Visual Breakdown for Cost Sensitivity by Cost Driver for Los Angeles, California

When cost sensitivity was revisited after applying weight constraints to payload, the different cost drivers showed increased sensitivity. Figure 9 shows Los Angles cost sensitivity after constraining the model to include deliveries 5 pounds or less. The other cities are in Appendix F.

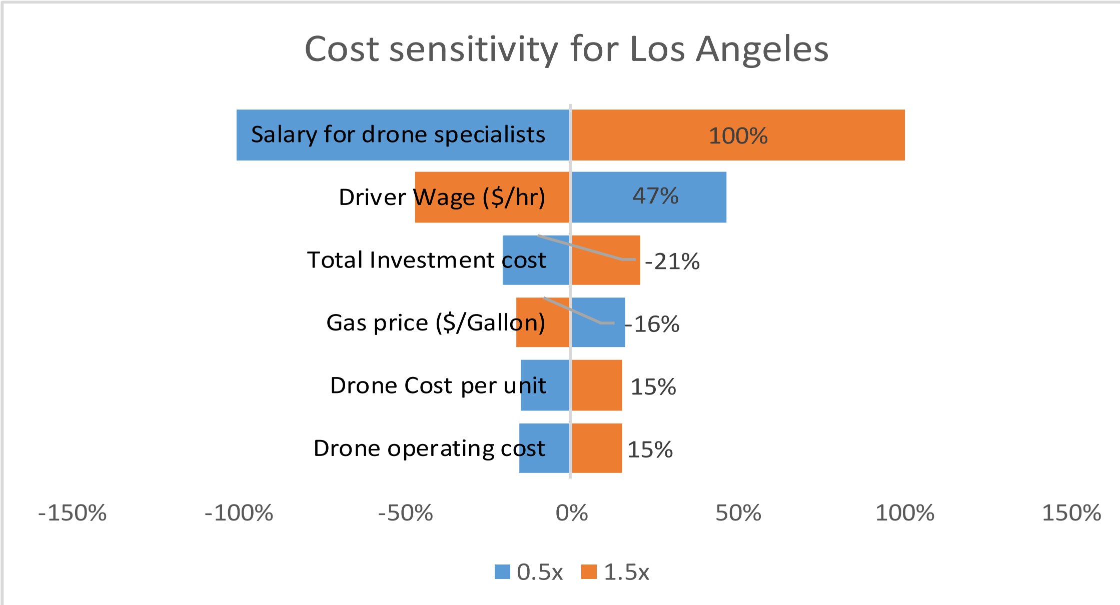

Figure 9: Visual Breakdown for Cost Sensitivity for Los Angeles, California with 5-pound Cargo Constraint

3.4 Collective Operational and Financial Sensitivity

The operational and financial scenarios were considered collectively to speculate a range for NPV in the next 5 years. For some cities, aligning all of the optimistic impacts is still not significant enough for delivery drones to make a positive impact. Other cities show positive NPV for the alignment of all positive circumstances.

3.4 Conclusion

Since there are no current investment possibilities to generate a positive NPV, 0% of deliveries are suitable for drone delivery. Rush and half day orders represent only a small portion of the sponsor company's business. The operational analysis found as many as 35% of deliveries are favorable for drone delivery with optimistic predictions. With cost reduction on delivery drone technology there is potential for cost effective drone delivery in some locations. Tables 3, 4, 5, and 6 detail the financial analysis in $1,000 units. For example, the 5-year future scenario has a corresponding NPV for the most likely scenario of ($481,000). Table 5 assumes every eligible incurs a $20 premium paid by the customer.

Table 3: Assumptions for 5-year Forecast Scenarios

Parameters	Current	In 5 years		
	Base case	Future Scenario 1	Future Scenario 2	Future Scenario 3
		Pessimistic Scenario	Most likely Scenario	Optimistic Scenario
Max Flying distance	17.5 miles	20 miles	25 miles	30 miles
Payload	5 lbs	10 lbs	15 lbs	20 lbs
Distance from airports	6 miles	4 miles	3 miles	2 miles
No. of drone specialists required	1 person handles 2 drones	1 person handles 2 drones	1 person handles 5 drones	1 person handles 10 drones
Total Investment cost	base case estimates based on regions	25% increase	25% reduction	25% reduction
Drone operating cost	base case estimates based on regions	25% increase	Same as base case	25% reduction
Gas price ($/Gallon)	3.5	25% reduction	Same as base case	25% increase
Driver Wage ($/hr)	20	Base case	25% increase	50% increase

Table 4: NPV for Drone Delivery Implementation at the Sponsor Company

City/Region	Current		In 5 years		
	Base case		Future Scenario 1	Future Scenario 2	Future Scenario 3
	Rush & half day order only	All orders	Pessimistic	Most likely	Optimistic
Los Angeles	$ (2,798)	$ (2,745)	$ (2,627)	$ (919)	$ 560
San Diego	$ (1,383)	$ (1,377)	$ (1,355)	$ (558)	$ 590
San Francisco	$ (1,454)	$ (1,439)	$ (1,427)	$ (428)	$ 339
Houston	$ (1,382)	$ (1,371)	$ (1,361)	$ (481)	$ (11)
Dallas	$ (1,422)	$ (1,421)	$ (1,464)	$ (734)	$ (669)

Table 5: NPV for Drone Delivery Implementation at the Sponsor Company given all Drone Deliveries come with a $20 Surcharge

City/Region	Current		In 5 years		
	Base case		Future Scenario 1	Future Scenario 2	Future Scenario 3
	Rush & half day order only	All orders	Pessimistic	Most likely	Optimistic
Los Angeles	$ (2,788)	$ (2,623)	$ (2,022)	$ 1,220	$ 6,037
San Diego	$ (1,381)	$ (1,361)	$ (1,238)	$ 582	$ 2,808
San Francisco	$ (1,445)	$ (1,405)	$ (1,263)	$ 53	$ 1,494
Houston	$ (1,377)	$ (1,338)	$ (1,184)	$ (1)	$ 1,072
Dallas	$ (1,412)	$ (1,411)	$ (1,402)	$ (565)	$ (298)

Table 6: Percentage of Deliveries Eligible for Drone Delivery

%	Current		In 5 years		
	Base case		Future Scenario 1	Future Scenario 2	Future Scenario 3
City/Region	Rush & half day order only	All orders	Pessimistic	Most likely	Optimistic
Los Angeles	0.04%	0.50%	2.47%	8.74%	22.38%
San Diego	0.03%	0.24%	1.84%	18.08%	35.19%
San Francisco	0.16%	0.61%	3.00%	8.77%	21.05%
Dallas	0.07%	0.51%	3.52%	10.30%	25.10%
Houston	0.10%	0.64%	3.46%	9.39%	21.18%

4. Discussion

Technology limitations, uncertain regulations, and method of implementation are just a few questions surrounding delivery drone investment. This section expands upon the operational and financial analysis. Through these lenses, consideration of drone feasibility for both the sponsor company and more generally for any industry considering drone usage are considered.

4.1 Considerations for Operational Analysis

As drone technology improves, the 0.2%-0.6% of the sponsor company's customer deliveries currently eligible for delivery will increase. For our analysis, a 17.5-mile (~28 kilometer) range was selected. Given the current technology on the market, this would be an ambitious distance for a system that delivers to the customer then returns directly to the sponsor facility. The limitation is battery power; if an investment in a hybrid technology were made, the 17.5-mile range would be easily achievable. The range selected is a good benchmark of performance. By the time a plan is set in motion, this range should be obtainable by most drone delivery companies. Part of the restriction on range comes from a weight limitation set by the FAA. Recently, the FAA has been accepting waivers for the weight limitation ("Part 107 Waivers Issued," n.d.). Another justification for the range is consideration for how the delivery is made. Customer service is important to the sponsor company. To implement the delivery drone and maintain customer satisfaction, using drones capable of flying to a delivery van may be the best subject for future research. While such a delivery network was beyond the scope of the analysis performed, the operational analysis tool can be adjusted to evaluate range benefits associated with drones interacting with a van fleet. The best part of the van fleet is the sponsor company does not need to sacrifice customer service or handle as many security threats using the van as a receiving station. Matternet is the authority on this technology; UPS has developed a partnership with the company ("Matternet," 2019).

Payload would be the first priority for refinement in future revisions. While volume is important to ensure a product could fit in a drone's cargo container, the delivery drone is much more sensitive to weight. Along with delivery drone range, the cargo capacity will increase as technology improves and adjustments to regulations occur.

Operating drones within close proximity to airports is another complicated subject. The 6-mile (~10 kilometers) distance chosen for the operational analysis is conservative for Class C or D airspace; however, the distance may not be conservative enough for Class B airspace. All of the cities considered in the analysis have Class B airspace. Class B is very congested and requires clearance before operating in. The airport proximity metric provides some situational awareness on challenges ahead in some locations, but it should not be considered as a binding constraint. The airport proximity gives a good feel for the potential lobbying power and support demand for drone specialists to interact with the FAA and airspace officials.

4.2 Considerations for Financial Analysis

All but one company in the delivery drone industry were non-responsive in regard to pricing inquiries. The only response received was in-person at a drone conference from Top Flight Technologies. They quoted a 1-unit price of $100,000 with a scalable cost to $35,000-$45,000 for a multiple drone purchase in October 2018. Recently they started to advertise implementation projects. They did not respond to a follow-up inquiry. While the prices seem high, they will certainly decrease with scale, technology improvement, and time. The best news on the subject is that cost analysis found drone investment to be a minimal consideration for financial feasibility. The most significant factor to consider was the cost of labor.

Currently, the title of drone specialist would wear many different hats and it would likely not be possible for an individual to cover all aspects of the job. The drone specialist is a pilot, a software specialist, a mechanic and inspector, and a lobbyist to name a few functions. Based on partnerships formed and advertisements from the major players in the delivery drone industry, it is likely the initial investment would require paying the manufacturing company for some time before sponsor company employees could fill the roles. There are some current waivers allowing drone operators to control up to 4 drones at a time ("Part 107 Waivers Issued," n.d.). Our analysis considers all drones can operate autonomously; the technology supports this assumption, but the regulations have not progressed far enough for this to be possible yet in the United States. Our best estimate for analysis was a 1:2.5 specialist to drone ratio. For tomorrow, the estimate is not conservative enough. For the near future, the estimate is appropriate. For the long range, this number could go as high as 1:10 or higher depending on the role of automation and challenges with operations. This subject is a considerable factor for future analysis. As in the sponsor company's current model, labor represents the most significant cost. While drone technology shows promise in terms of reducing labor, it will never eliminate the need.

4.3 Delivery Drone Practicality

The delivery drone has caught momentum in medical applications. Many of the companies that were launched to deliver goods have found themselves involved in medical delivery and applications ("Matternet," 2019). The waivers for operation seem to favor the exploration of medical applications. Considering the current activity, drones will likely need to prove themselves in medical applications before they expand to delivering products. The critical nature of medical equipment and supplies also fit the operational and financial implications of the analysis. Unlike parcel deliveries, most drone delivered medical supplies are going to remote areas within the range of drones where cost is virtually not a factor with someone's life on the line (Rosen, 2017).

The sponsor company is a master at customer service. While consumer preference for drone delivery is outside the scope of this analysis, the sponsor company's care and consideration of the customer are paramount. As previously mentioned, the technology of drones delivering to vans would be a good starting point for future analysis. Although there are complications in network modeling for this solution, there are undeniable benefits. The safety of the product and the customer satisfaction of a person delivering their product are still ensured. It also provides the advantage of decreasing delivery times. This presents an opportunity for future profit growth. Rather than looking at drones as a cost saving technology, they should be viewed as a profit driver.

Technology improvement will likely favor a wider range of climates in the future. Regulations will come and go as well as relax and constrain with time. Every time a drone makes the headlines because of an accident, the potential for overreaction occurs. This may present future risk and considerations for elevated insurance in the future. Given the silence from initial investors like Amazon and UPS, there are likely some other challenges are likely being considered before investing further.

5.0 Conclusion

The delivery drone comes with opportunity and risk. Drone delivery has limitations that will likely restrict it to certain areas and applications for some time. There is also risk that a newer technology will end the drone craze. Given the required alignment of favorable conditions, ambitious assumptions, and operation in restricted areas with favorable weather and business conditions, the outlook for cost reduction looks hindered. Although cost reduction does not seem significant, delivery drones have the potential to drive profit. The research conducted at MIT and in industry is measuring drone performance in terms of time and not cost. The sponsor company may have some opportunity to revisit this inquiry from a profit driving consideration versus a cost reduction. While the future is unclear, the technology does seem to be holding on. For the right applications, drones will continue to make headlines for the foreseeable future.

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Appendix A: A 20,000-foot view of airspace

Regulatory and non-regulatory airspace is a simple breakdown of the US airspace system. Non-regulatory airspace presents very few challenges. It can be thought of this as a large wide-open parking lot where parents take their children the first time they drive a car. While there are obstacles and risks, there are not many rules to comply with. Regulatory airspace requires getting on the road though. Drivers need a license, an understanding of traffic rules, and practice operating. Staying with the car analogy, the first place to start is with getting a license.

Just as cars have to be registered, delivery drones will likely need to be as well. The cost is currently inexpensive at $5 per drone valid for a 3-year period ("Certificated Remote Pilots including Commercial Operators," n.d.). For pilots and aircraft, a license, certification, and an airworthiness certificate are just a few requirements. A drone operator requires a license just like a pilot. The goal of the delivery drone is to be capable of full autonomous operation; however, the need for drone pilots will likely exist for some time. In the future, personnel programming drones will likely have to have a license and certification as well. Another requirement, an airworthiness certificate, is the FAA's way of determining if an aircraft is safe to operate in the skies. The requirement is not there for drones yet; however, the foundation is laid to get airworthiness certificates for drones. The requirement is currently mitigated by pilot's performing a preflight inspection of the drone and operating under the rules of the FAA's 14 CFR part 107. Given the momentum of the delivery drone industry, airworthiness certificates will likely be a requirement as they take a more active role in the airspace system. Traditionally, these costs are more expensive than traditional automotive licenses and certifications due to the specialized knowledge required. While costs are low now, they are important to watch for future analysis.

Within regulatory airspace, class airspace is important to understand. Here is condensed overview:

Class A: 18,000 feet MSL (mean sea level) and above. This is not relevant for drones.

Class B: Exists at the busiest airports in the world. Atlanta, Boston, Dallas, and Los Angeles are just a few. The skies within a 30-mile radius are carefully controlled. Significant flight planning and clearance to operate are required.

Class C: This includes most major airports and likely all of the cities the sponsor company operates in (if not Class B). There are communication requirements, flight planning, and some equipment required to operate in Class C. Although the airspace itself is usually only a concern within a 5-mile radius for the 400 ft AGL and below operations of a delivery drone, the rules and requirements begin to exist for a 20-mile radius.

Class D: Regional airports and military aviation represent many Class D airport locations. The airspace is generally near smaller cities where a control tower exists, but the air traffic volume is not a significant.

Class E: Regulated airspace used to control volume in high volume areas not in close proximity to an airport. Class E would likely not cause many challenges for delivery drones to operate in as it is mostly controlled as high altitudes.

Many other types of airspace exist, but the important aspect is to have an understanding that regulatory airspace will come with some requirements for communication, flight planning, rules, and agreements with local aviation authorities.

	Class A	Class B	Class C	Class D	Class E	Class G
Entry Requirements	ATC clearance	ATC clearance	Prior two-way communications	Prior two-way communications	Prior two-way communications*	None
Minimum Pilot Qualifications	Instrument Rating	Private or Student certification—local restrictions apply.	Student certificate	Student certificate	Student certificate	Student certificate
Two-Way Radio Communications	Yes	Yes	Yes	Yes	Yes, under IFR flight plan*	None
Special VFR Allowed	No	Yes	Yes	Yes	Yes	N/A
VFR Visibility Minimum	N/A	3 statute miles	3 statute miles	3 statute miles	3 statute miles**	1 statute mile†
VFR Minimum Distance from Clouds	N/A	Clear of clouds	500' below, 1,000' above, 2,000' horizontal	500' below, 1,000' above, 2,000' horizontal	500' below,** 1,000' above, 2,000' horizontal	Clear of clouds†
VFR Aircraft Separation	N/A	All	IFR aircraft	Runway operations	None	None
Traffic Advisories	Yes	Yes	Yes	Workload permitting	Workload permitting	Workload permitting
Airport Application	N/A	• Radar • Instrument approaches • Weather • Control tower • High density	• Radar • Instrument approaches • Weather • Control tower	• Instrument approaches • Weather • Control tower	• Instrument approaches • Weather	• Control tower

*Exception: temporary tower or control tower present
**True only below 10,000 feet
† True only during day at or below 1,200 feet AGL (see 14 CFR part 91)

AGL—above ground level
FL—flight level
MSL—mean sea level

https://www.cfinotebook.net/notebook/national-airspace-system/national-airspace-system

Appendix B: Who is making delivery drones?

Appendix B explains the landscape of delivery drone companies currently on the market. Top Flight Technologies, Flytrex, Flirtey, X, and Matternet all have different advantages and disadvantages. While some companies have been more successful than others, each company has special technology and limitations to consider.

Top Flight Technologies

Top Flight Technologies has a highly capable product; however, its hybrid powerplant and weight limit over the 55-pound US FAA regulation make it challenging.

http://www.tflighttech.com/solutions/60-day-mission-ready-delivery-program.html

Flytrex

Flytrex has a great solution, but their flagship project has been delivering food to golfers on a course.

They did not respond to my inquiry regarding pricing.

https://www.flytrex.com

Flirtey

Flirtey is a leader in the delivery drone industry conducting work with Dominos, 7-Eleven, and NASA. They have recently started working delivering AEDs where delivery drones seem to be finding most of their momentum. They did not respond to my inquiry regarding pricing.

https://www.flirtey.com

X

X is more of a research company compared to other delivery drone manufacturers, but they have a good design and are active in the delivery drone market with Project Wing.

https://x.company

Matternet

Matternet seems to be the company to watch with active relationships with UPS, Boeing, and Mercedes. Their partnership with Mercedes showcases a van that is capable of receiving drones during delivery routes for expedited delivery services. They are also active internationally in Switzerland where drones have significant momentum. Like their competition, they seem to be branching toward medical applications. Matternet did not respond to my inquiry regarding pricing.

https://mttr.net

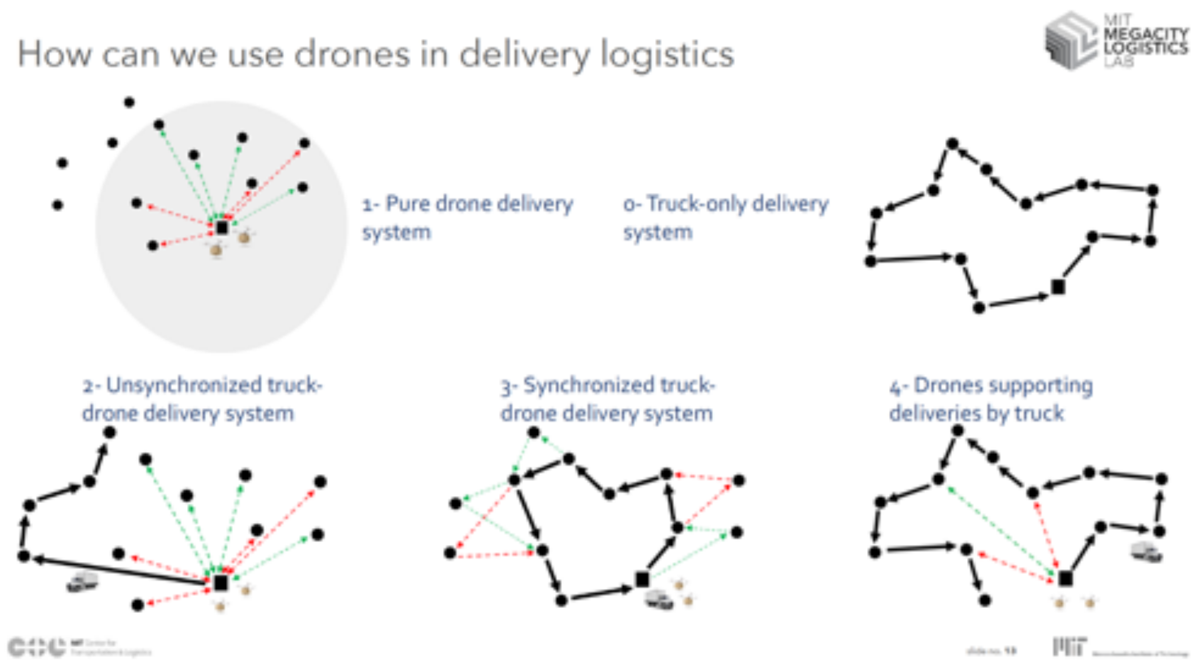
Amazon

Amazon may be the first company to implement delivery drones at scale. The two images above appear to be newer and more sophisticated than the model depicted in Figure 1. Their designs are intriguing as they show research in both short range (upper) and long range (lower) designs.

https://www.amazon.com/Amazon-Prime-Air/b?ie=UTF8&node=8037720011

Appendix C

The intent of Appendix C is to showcase some of the research being conducted in the MIT Megacity Logistics Lab. The assessment performed for the sponsor company assumes a pure drone delivery system. A potentially cost-effective solution for the future exists for the sponsor company if the drones supporting delivery by truck becomes popular.



The image above was provided by Dr. Mohammad Moshref-Javadi after a presentation given at MIT on December 3, 2018.

Appendix D

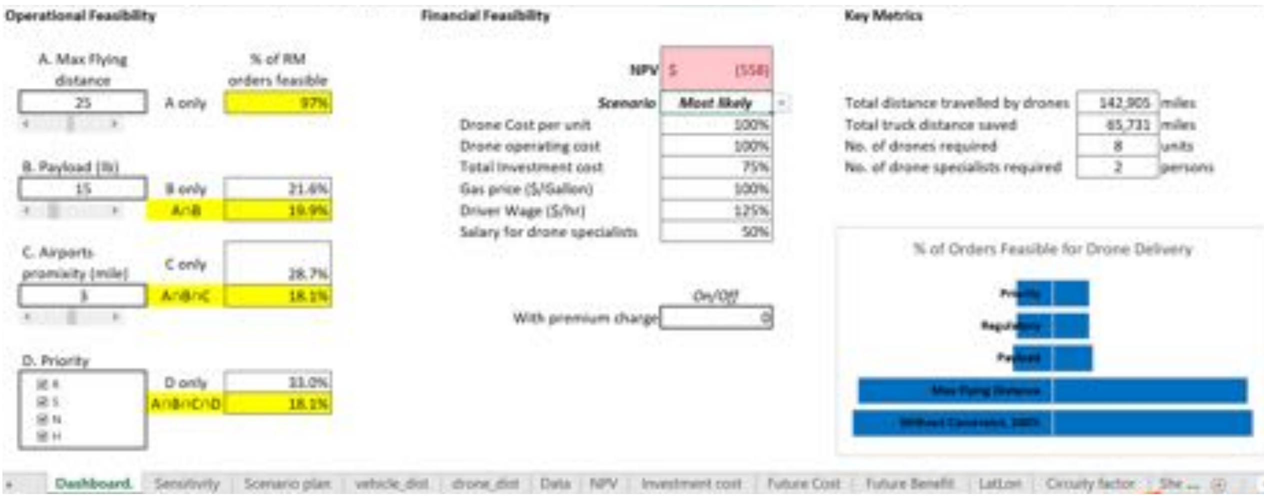


Figure D1: Operational and Financial Feasibility Analysis Tool

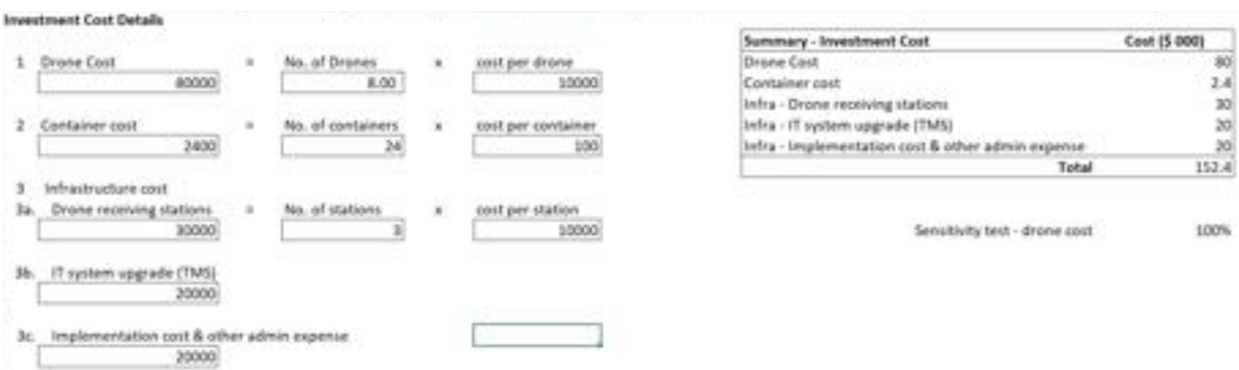


Figure D2: Investment Cost Analysis Tool

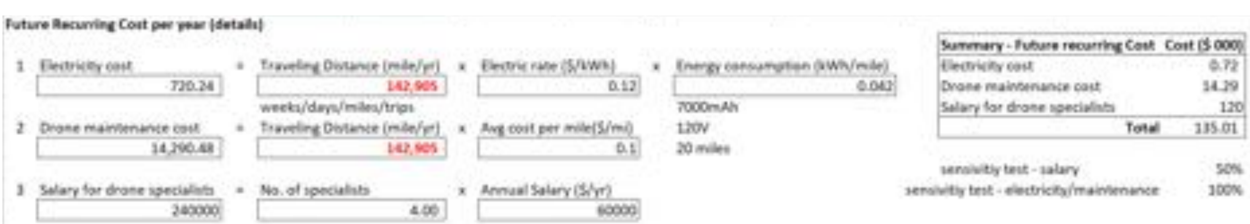


Figure D3: Future Cost Analysis Tool

Figure D4: Future Benefit Analysis Tool

Appendix E

List of Key Assumptions for Financial Analysis

Initial investment cost assumptions:

- Drone price = $10,000 per unit
- Container price = $100 per unit, 3 cargo containers per drone
- Drone station price = $10,000 per location (one location per depot)
- Implementation, system integration, and other administration cost = $40,000
- The useful life of drones and containers is 5 years, which means they need to be replaced every 5 years.

Drone operating cost assumptions:

- Annual salary for drone specialist = $60,000 per person.
- Drone maintenance cost (including battery, repairs, etc.) = $0.10 per mile
- Energy and maintenance cost are calculated using cost per mile multiply by total expected distances to be travelled by drones. In this project, the great-circle distance function is adopted for distance calculation between 2 points.

  Drone travel distance per trip, $d = \arccos(\sin[LAT\ A] \cdot \sin[LAT\ B] + \cos[LAT\ A] \cdot \cos[LAT\ B] \cdot \cos[LONG\ A - LONG\ B]) \cdot 3959 \times 2$

  Where:

  LATi = Latitude of point i in radians,
  LONGi = Longitude of point i in radians,

Vehicle cost saving assumptions:

- Gas price = $3.50 per gallon
- Energy consumption = 10 mile per gallon
- Driver's wage = $20 per hour
- Average distance traveled per hour = 25 miles per hour
- Vehicle maintenance cost = $0.20 per mile
- Due to absence of actual distance traveled by vehicles from depots to every customer location, the potential reduction in total vehicle distance traveled are estimated based on the following methods and assumptions:

1. Since vehicle travels through road networks with obstacles, hills and one-way traffic, the road distances calculated from distance functions (i.e. Great-circle distance) need to be adjusted with a multiplier called circuity factor. On the other hand, a drone which flies in an almost straight line to destination has a significant advantage in saving time and distance traveled. Hence, part of the savings on distance traveled by vehicle can be described as distance between traveling straight line and through road network between 2 points, $D_{circuity}$ as follows:

   D_c = Great-circle distances between 2 points x (vehicle circuity factor - drone circuity factor) x 2

   Where drone circuity factor = 1.0, assuming drones fly straight line between 2 points.

Vehicle circuity factor varies in different cities as follows[5]:

Metropolitan Area	Circuity Factor
Dallas	1.236
Houston	1.263
Los Angeles	1.236
San Diego	1.393
San Francisco	1.393
Toronto	1.3

2. When a package is taken out from the original transportation plan and delivered by drone, the total distance of a vehicle traveled may be reduced. Besides, the vehicle now has an extra capacity to deliver other packages. This could save a whole vehicle trip once there are sufficient number of packages to be delivered by drone cumulatively. For simplicity, we assume that there is always a new package to replace the package that is delivered by drone, in other words, the vehicle will only depart if a new package is available to replace the empty space. The cumulative distance saved, $D_{consolidate}$ is derived based on the following formula:

$$D_{consolidate} = \sum \frac{v}{C} . D_r$$

Where v = volume (or weight) of package which delivered by drone
C = total volume (or weight) of package in a vehicle for every route
D_r = total distance travelled by vehicle for every route

Hence, the potential reduction of vehicle distance travelled, $D = D_{circuity} + D_{consolidate}$

5 (Giacomin & Levinson, 2015)

Appendix F

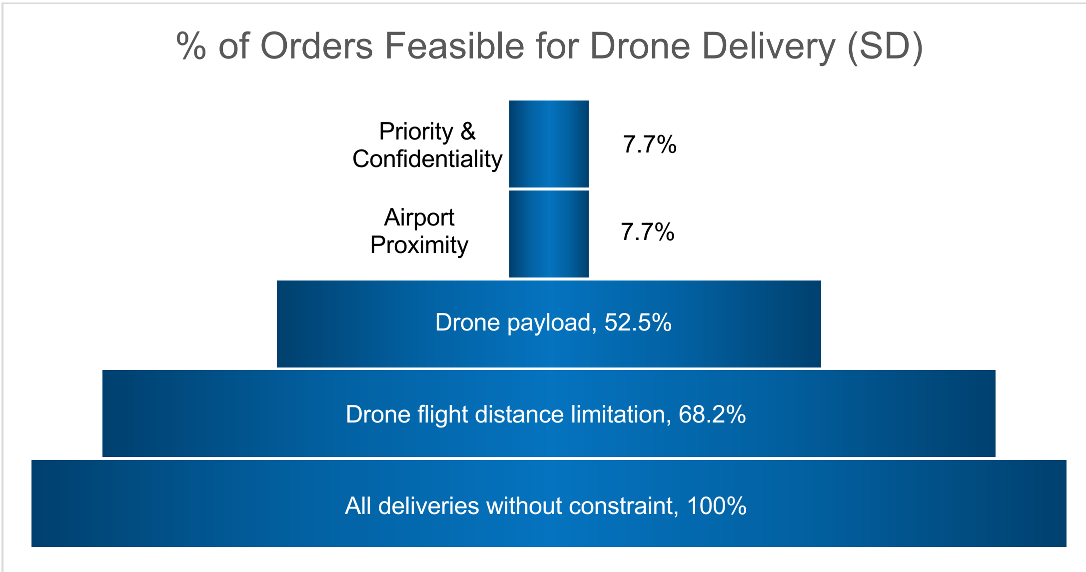


Figure F1: Operational Feasibility of the Delivery Drone for San Diego, California (All 1.2 cubic feet packages)

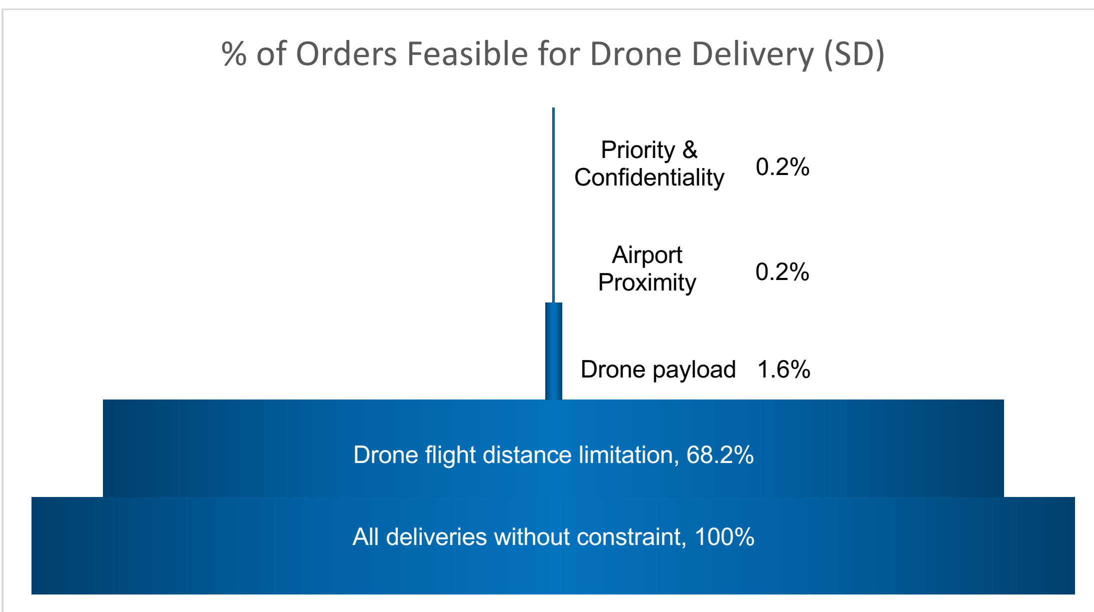


Figure F2: Operational Feasibility for San Diego, California Adjusted for Average Weight Distribution of 1.2 Cubic Feet or less Cargo ≤ 5 pounds

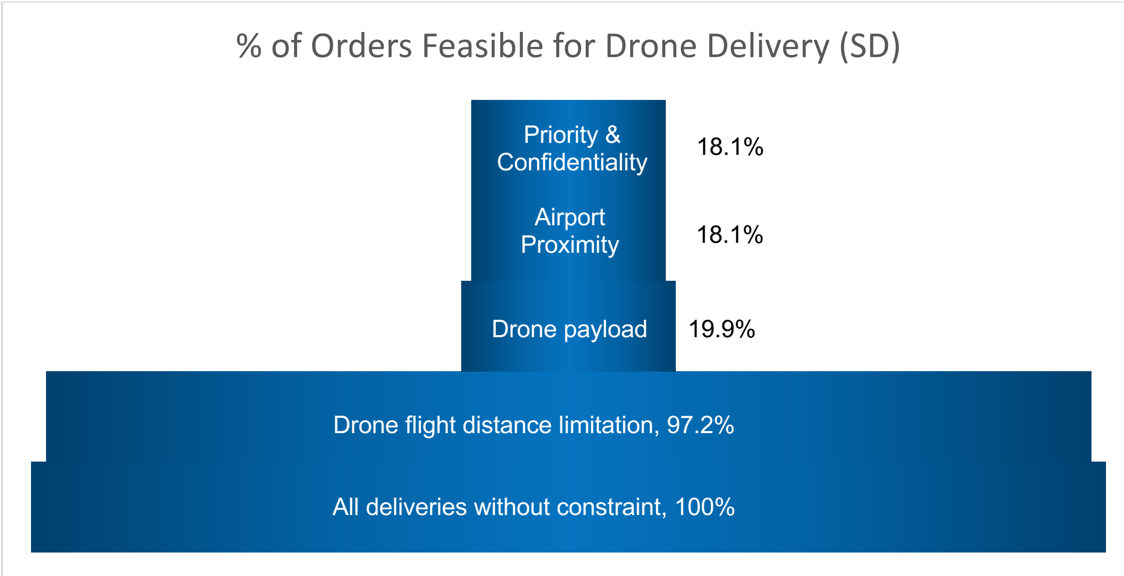


Figure F3: Operational Feasibility for San Diego, California Adjusted for Average Weight Distribution of 1.2 Cubic Feet or less Cargo ≤ 20 pounds

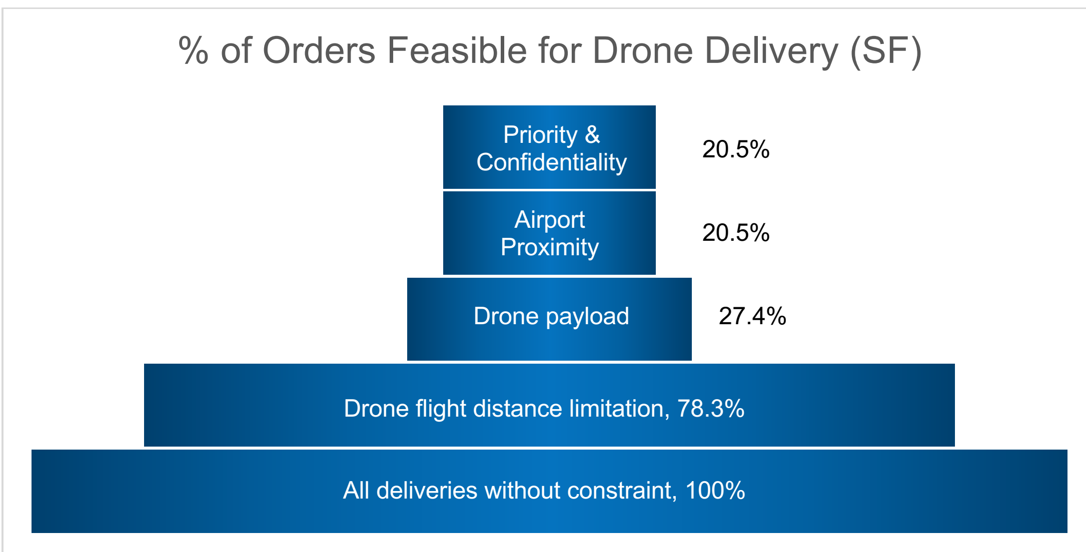


Figure F4: Operational Feasibility of the Delivery Drone for San Francisco, California (All 1.2 cubic feet packages)

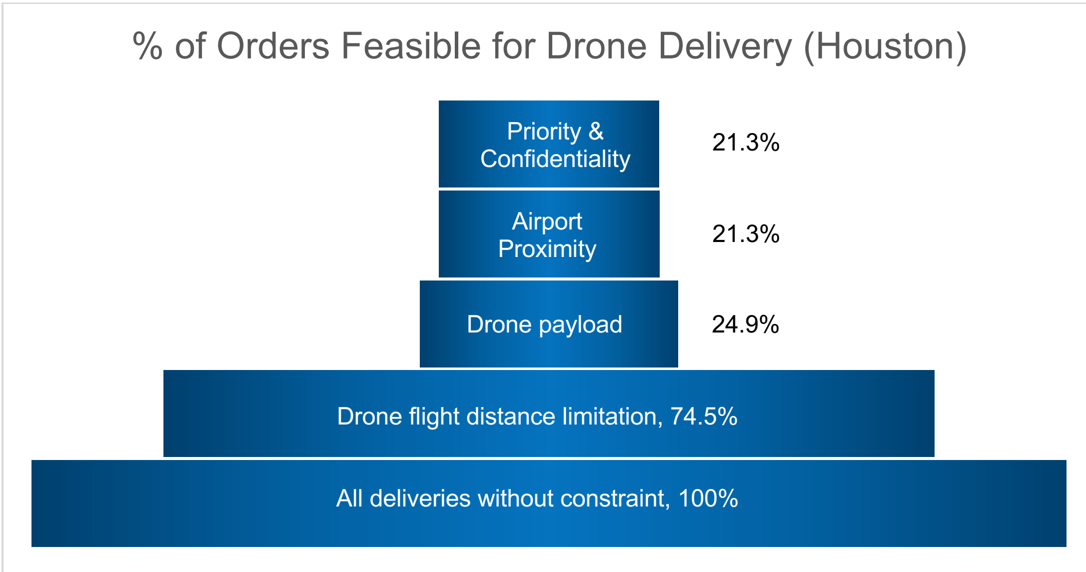


Figure F5: Operational Feasibility of the Delivery Drone for Houston, Texas (All 1.2 cubic feet packages)

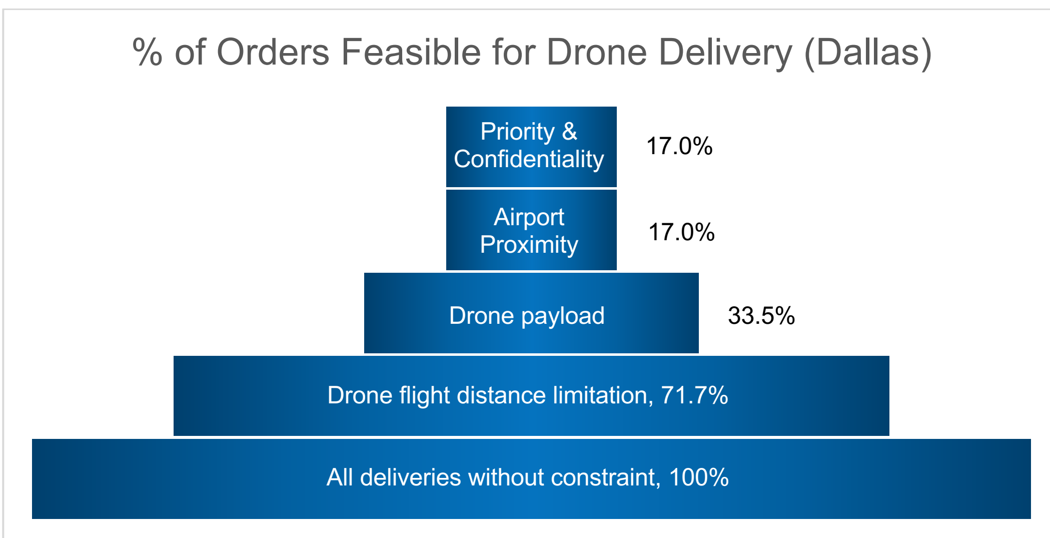


Figure F6: Operational Feasibility of the Delivery Drone for Dallas, Texas (All 1.2 cubic feet packages)

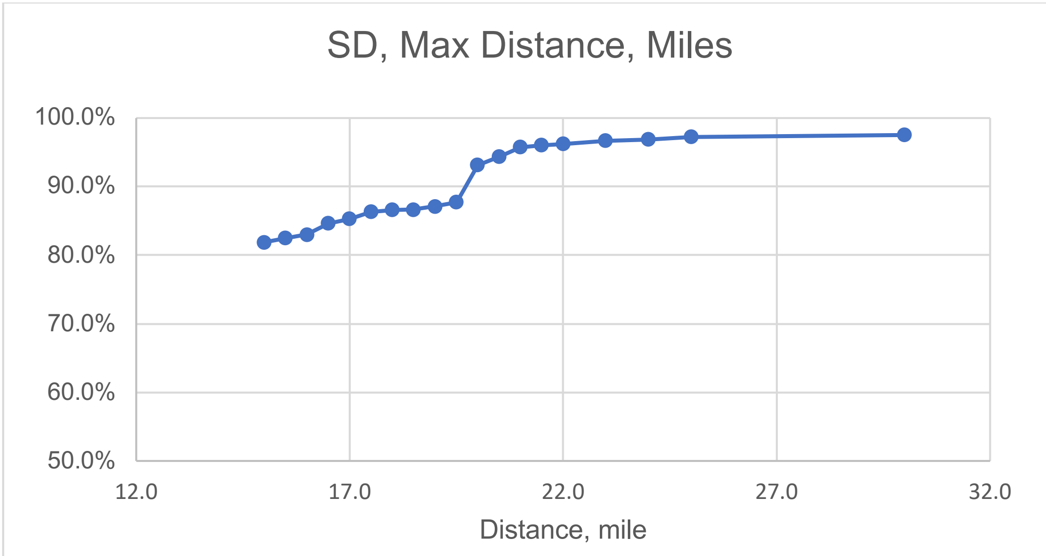


Figure F7: Max Flight Distance Sensitivity Analysis for San Diego, California

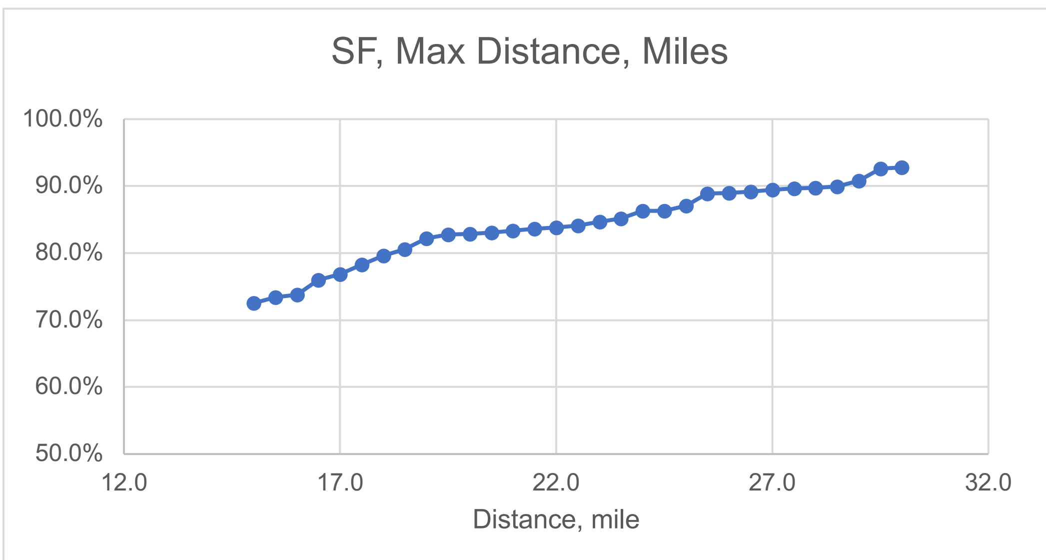


Figure F8: Max Flight Distance Sensitivity Analysis for San Francisco, California

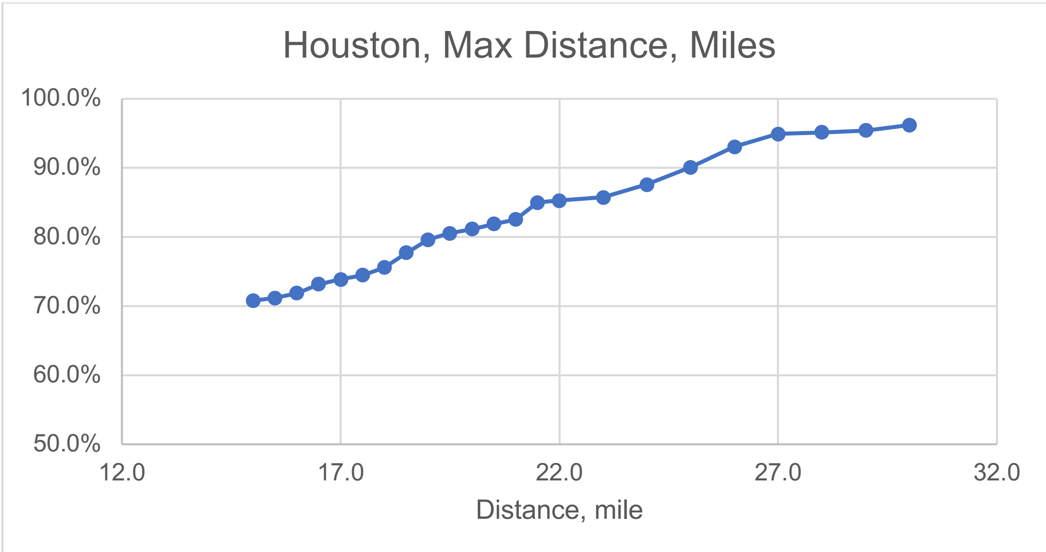


Figure F9: Max Flight Distance Sensitivity Analysis for Houston, Texas

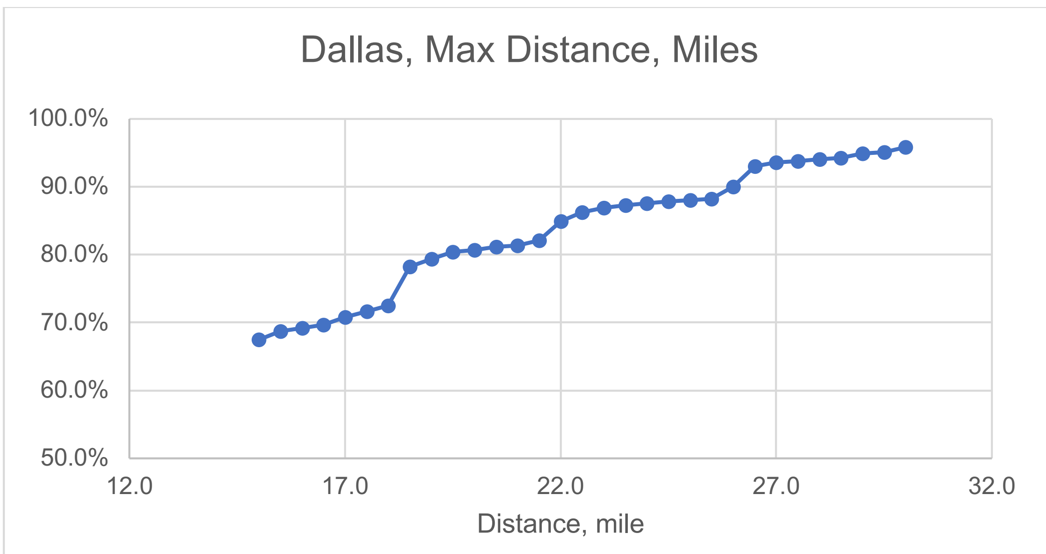


Figure F10: Max Flight Distance Sensitivity Analysis for Dallas, Texas

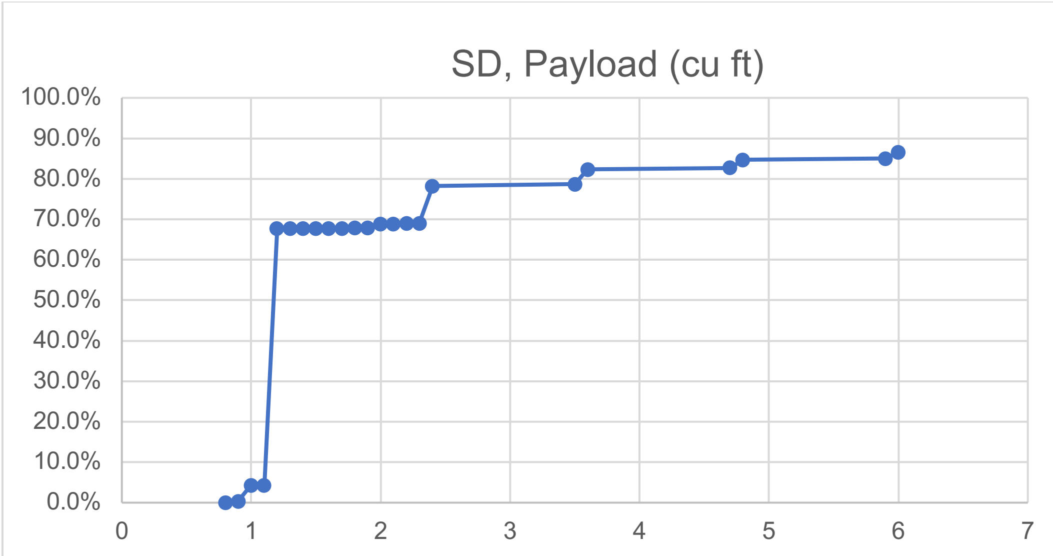


Figure F11: Payload Sensitivity Analysis for San Diego, California

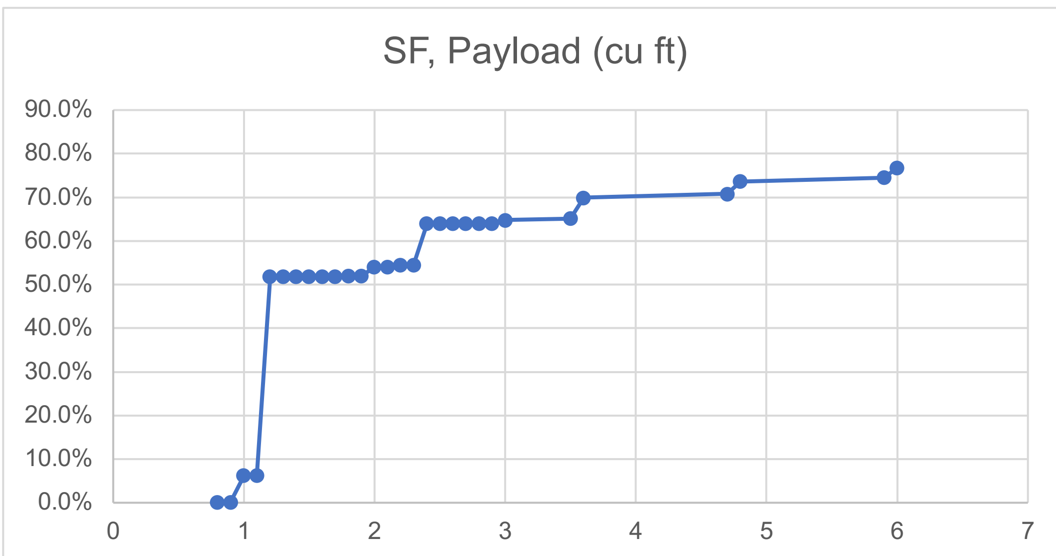


Figure F12: Payload Sensitivity Analysis for San Francisco, California

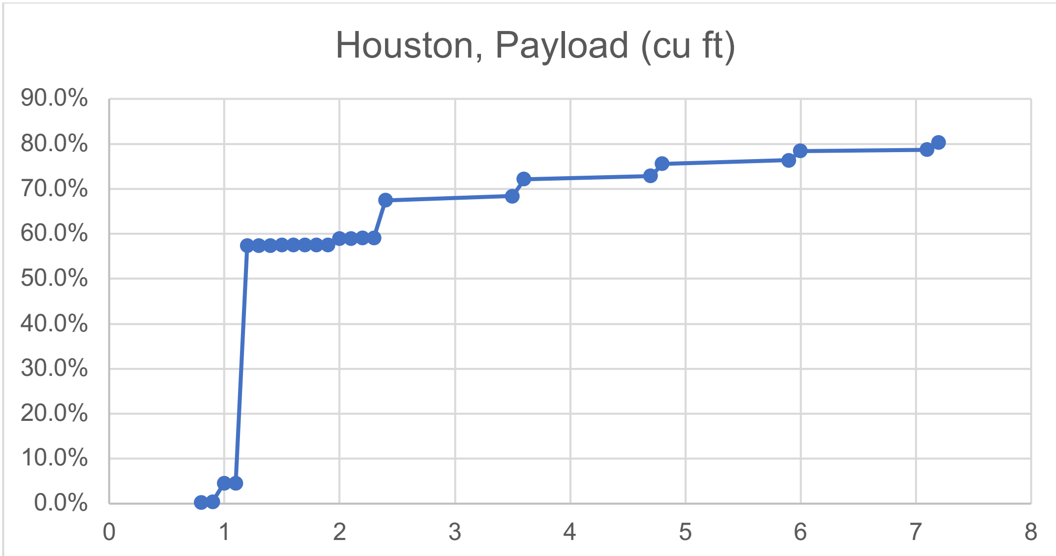


Figure F13: Payload Sensitivity Analysis for Houston, Texas

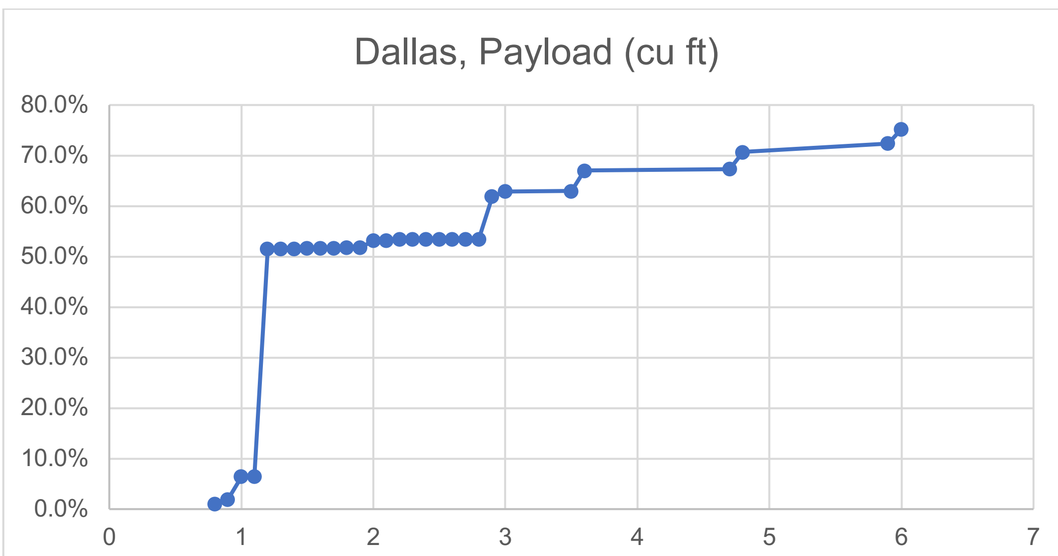


Figure F14: Payload Sensitivity Analysis for Dallas, Texas

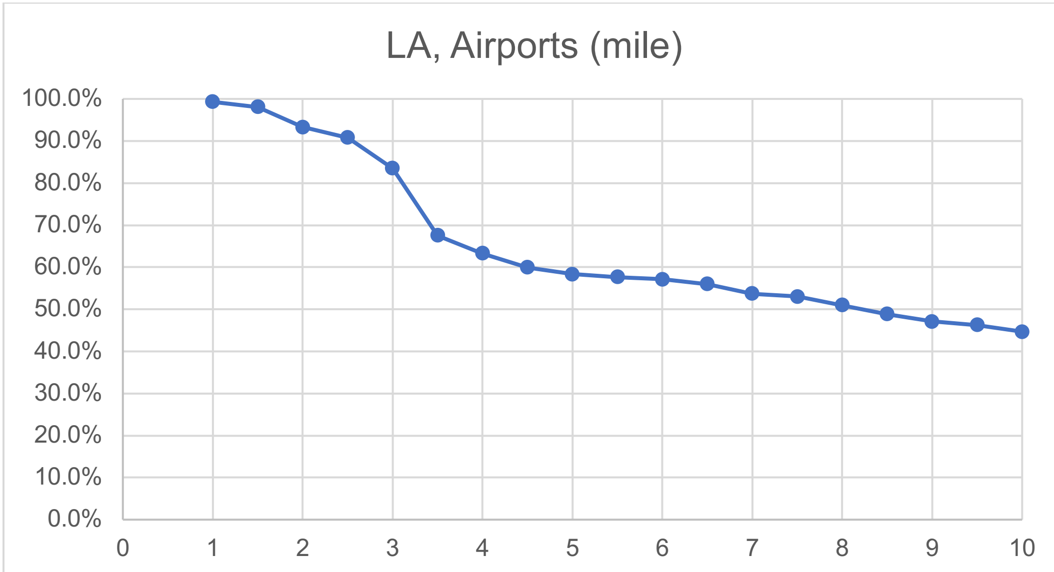


Figure F15: Percentage of Customers > X miles from a Major Airport in Los Angeles, California

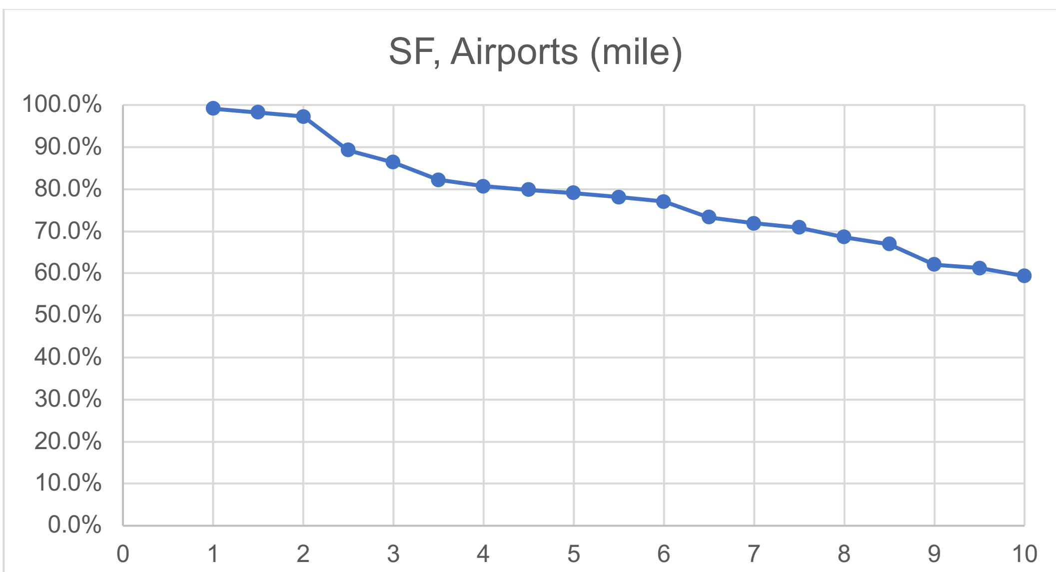


Figure F16: Percentage of Customers > X miles from a Major Airport in San Francisco, California

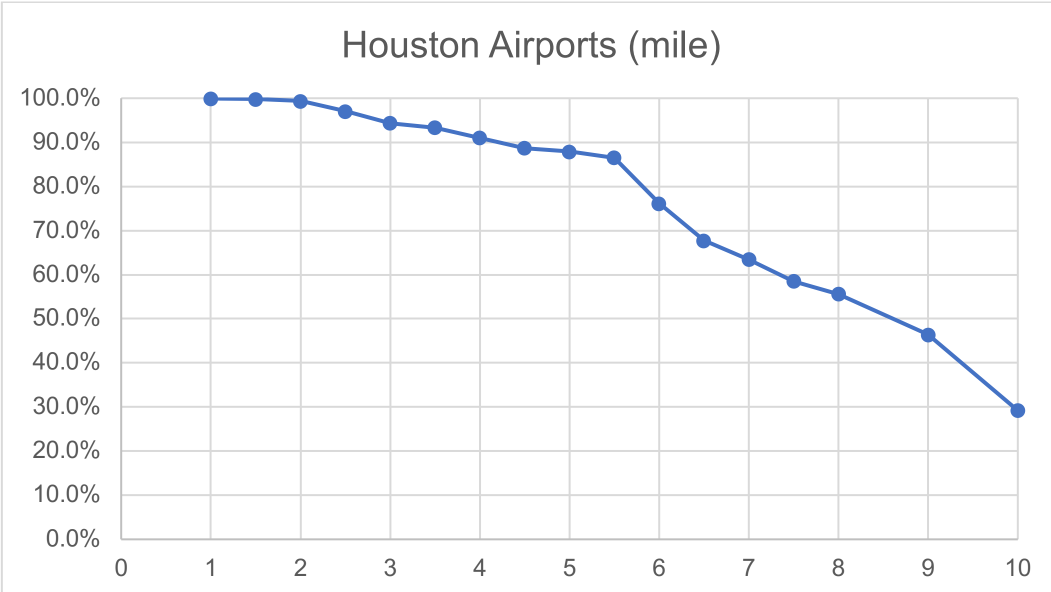


Figure F17: Percentage of Customers > X miles from a Major Airport in Houston, Texas

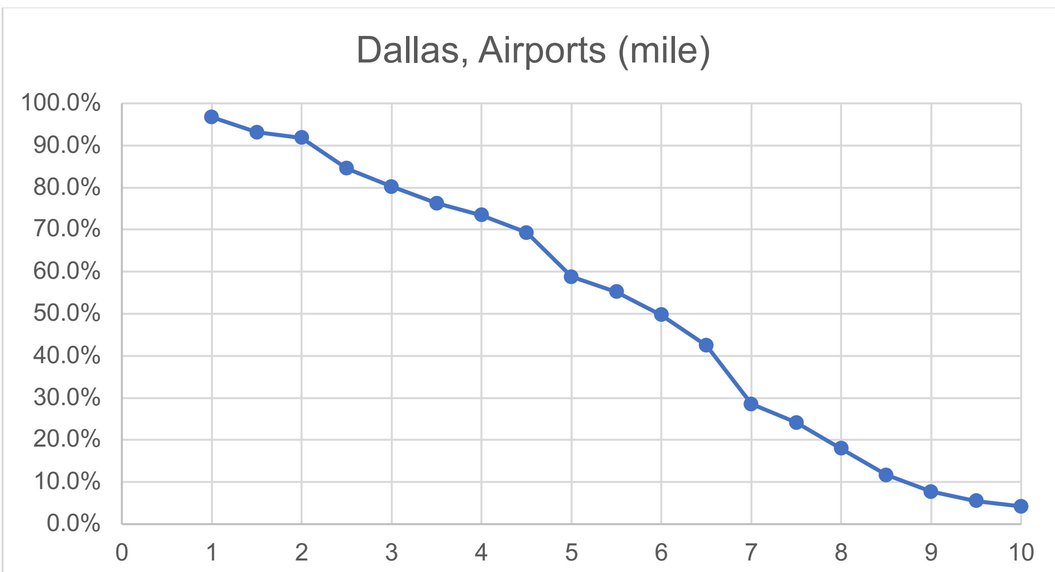
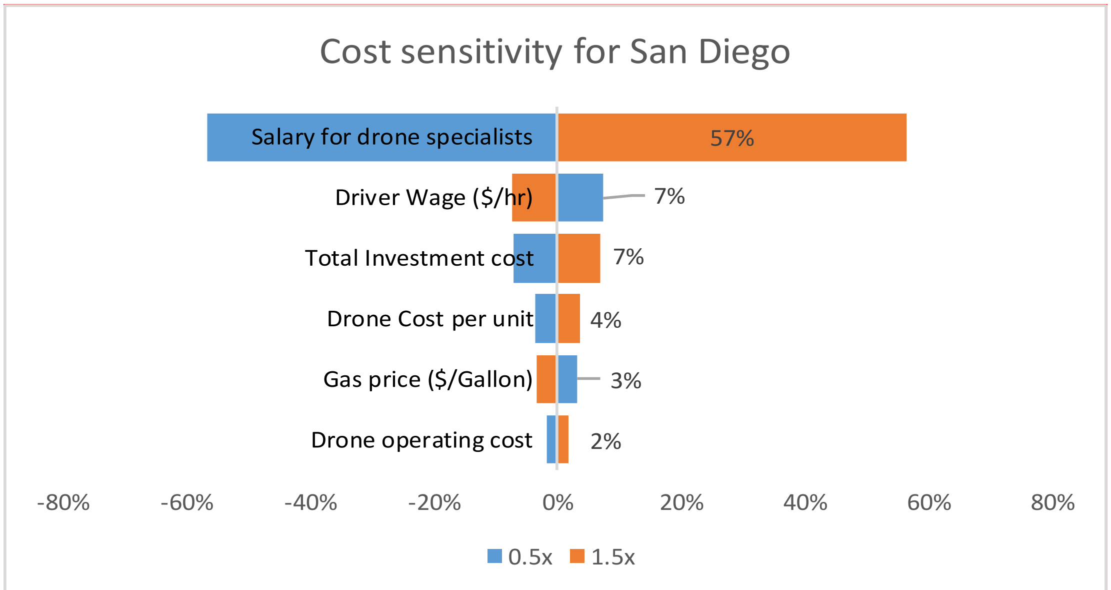


Figure F18: Percentage of Customers > X miles from a Major Airport in Dallas, Texas



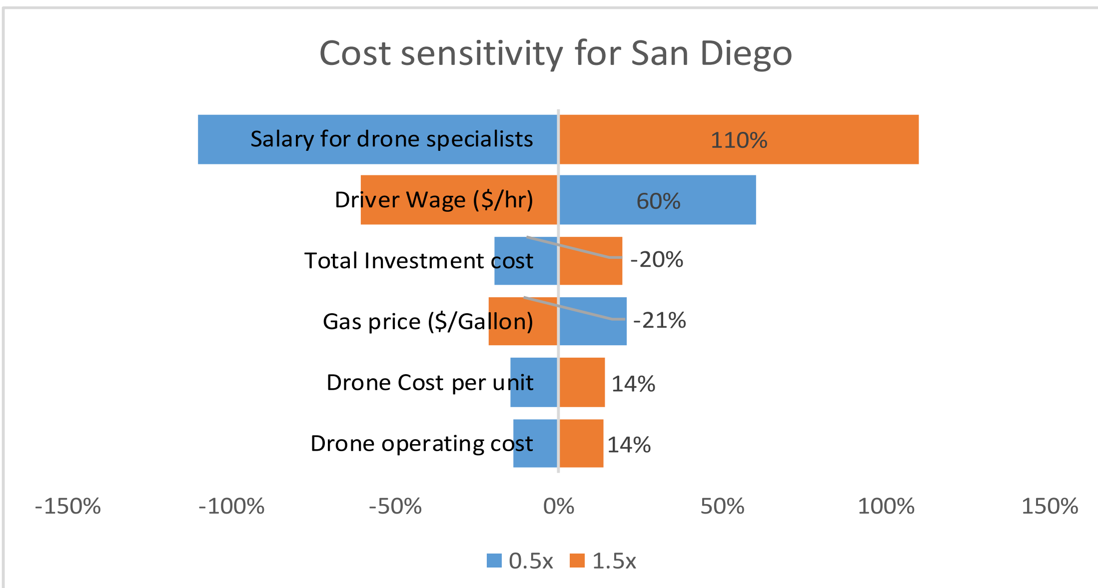
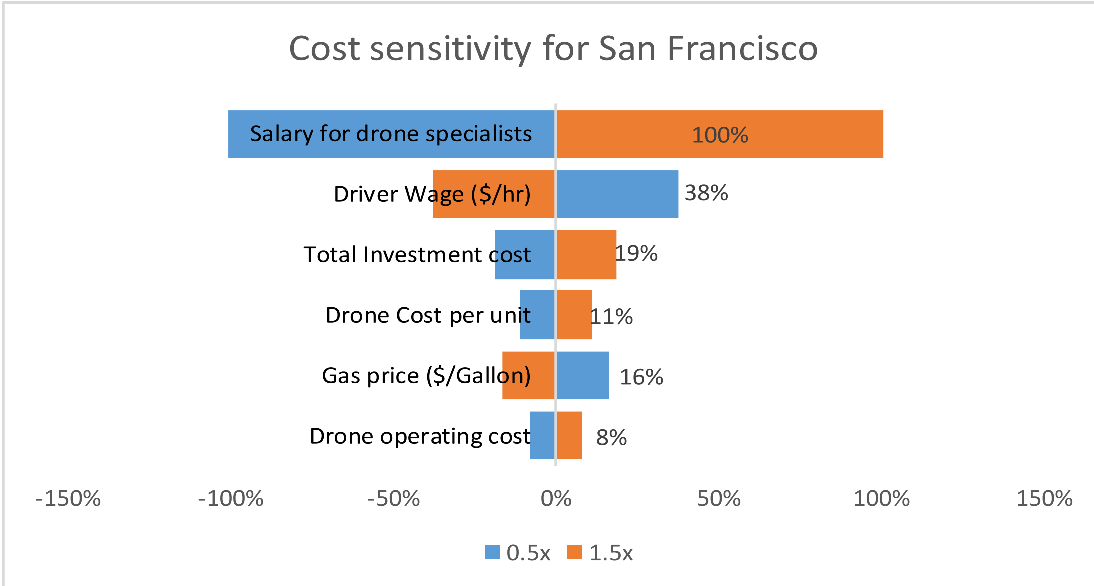


Figure F19: Visual Breakdown for Cost Sensitivity by Cost Driver for San Diego, California
All 1.2 Cubic Feet Cargo (Top)
All 1.2 Cubic Feet Cargo ≤ 5 pounds (Bottom)



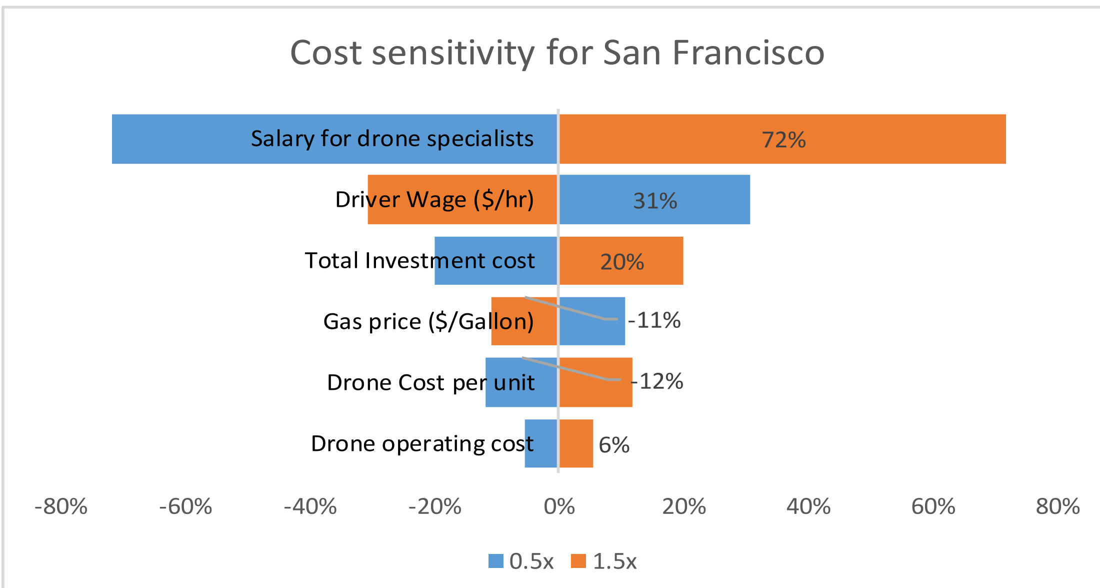
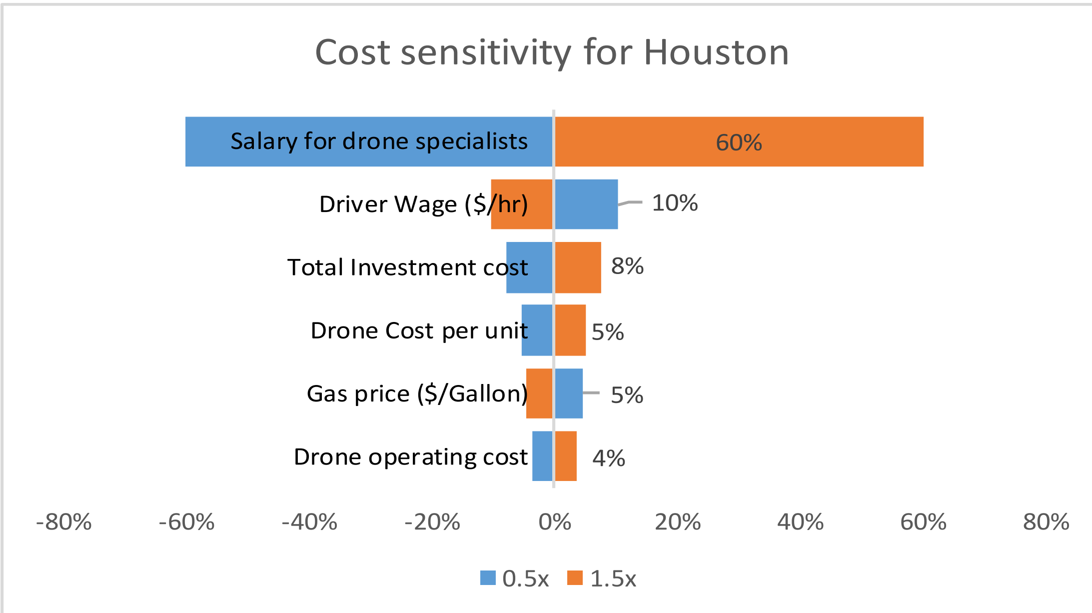


Figure F20: Visual Breakdown for Cost Sensitivity by Cost Driver for San Francisco, California
All 1.2 Cubic Feet Cargo (Top)
All 1.2 Cubic Feet Cargo ≤ 5 pounds (Bottom)



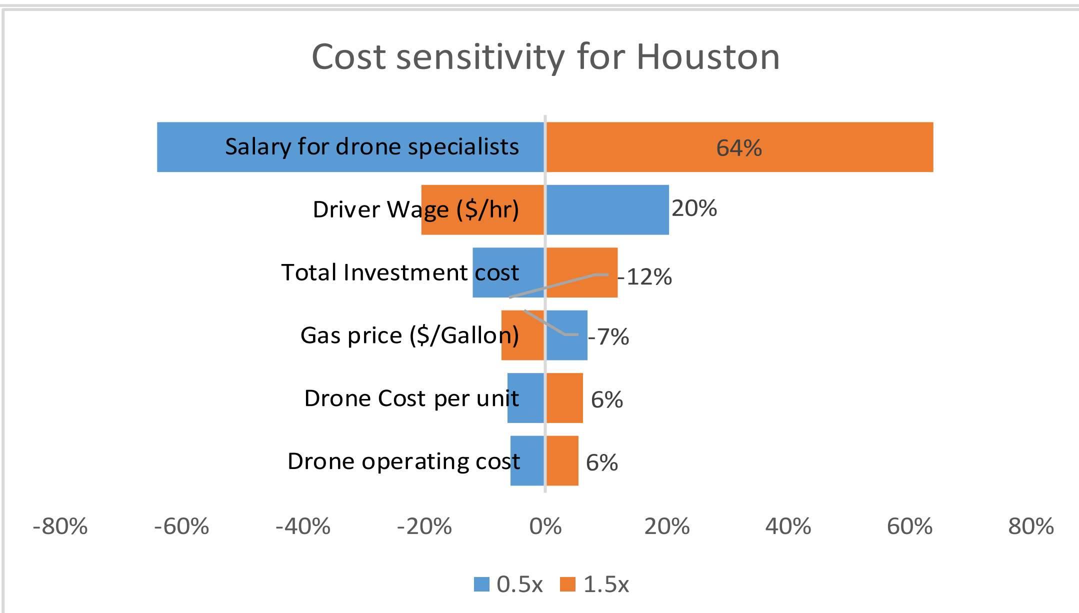
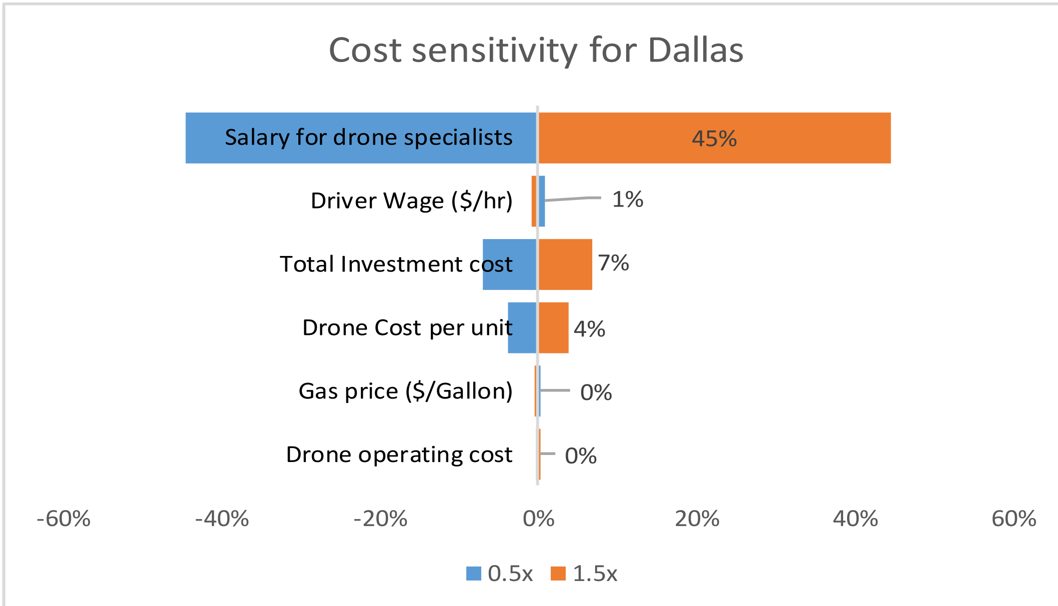


Figure F21: Visual Breakdown for Cost Sensitivity by Cost Driver for Houston, Texas
All 1.2 Cubic Feet Cargo (Top)
All 1.2 Cubic Feet Cargo ≤ 5 pounds (Bottom)



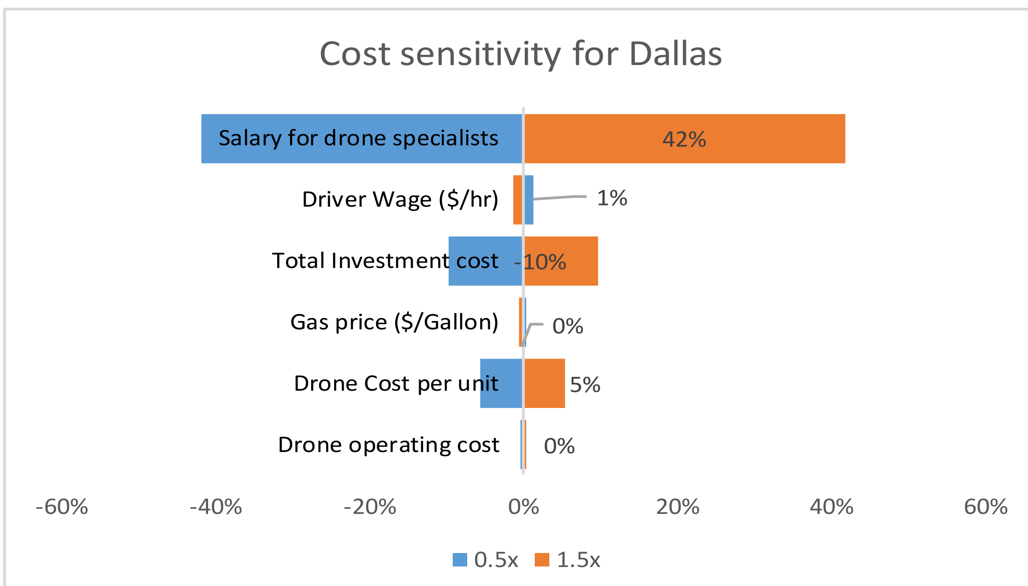


Figure F22: Visual Breakdown for Cost Sensitivity by Cost Driver for Dallas, Texas
All 1.2 Cubic Feet Cargo (Top)
All 1.2 Cubic Feet Cargo ≤ 5 pounds (Bottom)