Team 19 Project Report

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Executive Summary

While crewed trucks currently serve the final fulfillment leg over the ground, this project explores the application of drone technology to last-mile delivery through the air. Delivery from terminal routing hubs to suburban residential areas suffer from unpredictable variation in shipping demand over time and distance domains and incur exorbitant operating costs and fuel emissions. Growing volumes of e-commerce sales necessitate more reliable, sustainable, and timely delivery service. Recent, rapid advancements in autonomous flight vehicles may create scalable synergies with existing delivery infrastructure so that economies of scale are achieved at the varying population densities of the last mile.

This report details the design and analysis of a drone delivery system proposed to conduct last-mile delivery of packages more effectively and efficiently than current truck methods. A comprehensive review of the last-mile logistics problem, as well as past, present, and proposed delivery solutions, was conducted. Stakeholders in cargo transportation and airspace governance were identified by name and evaluated by need. Customer attributes were tabulated and evaluated to produce an extensive list of engineering specifications for a drone delivery system. Technical requirements were assigned a metric and target value, traced to customer needs, and ranked by importance to overall system functionality. Creation of functional flow and concept of operations diagrams aided in exploring the expected operational environment to iterate upon customer needs and engineering specifications. Customer attributes and system specifications were then correlated and compared in a House of Quality to clarify relationships between requirements parameters and guide subsequent design ideation. Through a creative yet organized process, a variety of concepts for both vehicle configuration and payload release were generated. An iterative and careful evaluation of concepts in Pugh matrices converged to a single design for the drone delivery system. This selected concept was further analyzed in financial performance and operational risks through a spreadsheet model and fault and event trees, respectively. A failure modes, effects, and criticality analysis (FMECA) discovered gaps in concept robustness for mitigating in latter design states while the economic analysis confirmed a promising business case for further pursuing the project.

Environment exploration, design reasoning, and concept evaluation, as well as their accompanying tables, plots, and images, are compiled. The following contains preliminary vehicle configuration and payload release designs and accompanying analysis for a drone delivery system striving to quickly, safely, and cheaply address logistics inefficiencies across the last mile.

1. Introduction

1.1 Background:

Often the most expensive and inefficient stage of a logistics network, last-mile delivery is the movement of a product from a distribution hub to the consumer. This final leg of order fulfillment is financially and technically challenging due to the geographic dispersion of destinations, time expectations of customers, growing popularity of e-commerce, and congestion of ground traffic. Same-day delivery and crowdsourcing transportation trends have further complicated the logistics of last mile delivery. However, this final leg of delivery is of paramount importance to logistics companies as it is the sole point of physical interaction between the consumer and company brand.

In recent years, cross-country shipping standards have dropped substantially from 3-4 days to a mere 2 days, with widespread same-day fulfillment on the horizon. Speedy shipping has been accelerated from a matter of preferred convenience to that of expected necessity. In addition to greater timeliness, stress on last-mile delivery systems has also been compounded by drastic volume increases. Projected to rise at roughly 14% year over year through the next decade, e-commerce sales already contribute nearly $600 billion to the American economy alone [1]. While comprising the smallest travel distance, the final leg of package delivery accounts for the largest travel cost share as varying demand densities and route structures hinder achieving economies of scale over the last mile. Relative to other shipping expenses of line hauling, hub sorting, and spoke collection, last-mile delivery causes an astoundingly disproportionate 53% of total fulfillment costs [2]. More so than just reducing costs, improving terminal delivery service would generate additional revenue as 28% of the e-commerce market has indicated willingness to pay extra for same-day or guaranteed-time shipping [2]. Exacerbated by diverging customer demands and infrastructure capacities, the last-mile delivery market is financially ripe for technological innovation through cross-industry application of advanced aerospace solutions.

Many legacy cargo carriers, namely DHL, UPS, and FedEx, have established partnerships with drone delivery startups and have commenced experimental trials. Additionally, conglomerates such as Amazon, Alibaba, and Alphabet are internally developing drone systems for distribution of or integration with their own products. Most advanced in regulatory certification are the ‘Horsefly’ joint venture between UPS and Workhorse and the ‘Project Wing’ program from Google: Horsefly has deployed drones from retrofitted delivery trucks on suburban routes in Florida and Project Wing has flown thousands of packages during extended testing in Australia and Virginia [4,5]. Autonomous, aerial transportation of medical supplies ranging from human organs and prescription drugs to automatic defibrillators and exotic antivenoms is also being pursued by companies around the world, such as Flirtey and Zipline. Unmanned, ground delivery of packages and food is a much more crowded and mature space: closer to campus, food delivery is now being conducted by Starship robots.

1.2 Motivation:

As fast and even free shipping become ubiquitous among ever-increasing volumes of e-commerce transactions, small UAVs capable of quick package delivery have greatly enhanced appeal.

With traditional infrastructure comprising of aircraft to transport goods between hubs, semi-trucks to transport goods between warehouses, and vans to transport goods to consumers, drones are a logical complement to existing logistics networks. Drones are well suited to serve the highly dynamic, lower density last-mile delivery routes due to their sizes, speeds, ranges, and batteries. Applying autonomous air vehicles to deliver various cargo offers improvements across multiple, key dimensions of shipping: aerial platforms are not susceptible to street traffic congestion and may thus offer quicker delivery; robotic systems do not require a human operator and may thus diminish operating costs; and drones are commonly powered by electric batteries and may thus reduce carbon emissions. Synergized with an overarching transportation infrastructure, a fleet of agile drone platforms can directly increase delivery service quantity, in terms of fulfilled orders, and quality, as measured by fulfillment speed. Operating at a potentially cheaper price point, drone systems may also open additional revenue opportunities through same-day, slot-scheduled, or sensitive material deliveries. Application of drones to last-mile package delivery best leverages their favorable speed and power characteristics, enhancing the time efficiency and cost effectiveness of last-mile delivery operations.

1.3 Mission:

Seeking to provide an economically and technologically advantageous alternative to traditional last mile logistics, Team 19 has designed a drone delivery system capable of transporting small packages from local warehouses to consumer households. A product line derived from such a last-mile package delivery drone also enjoys feasible applications to the delivery of other goods, such as food and medicine, over other geographic scopes.

Mission Statement:

To develop a package delivery system that performs last-mile business-to-consumer delivery of goods in a faster, safer, and cheaper manner than current ground shipping methods.

1.4 Schedule

Team 19 planned, prioritized, and executed workflow over approximately nine weeks that were allotted for the early development of this project. The team created a Gantt chart to ensure timeliness and assign responsibilities. The first two weeks were spent conducting a literature review of the last-mile issue in package delivery; this consisted of defining the problem statement, exploring the problem scope, analyzing existing solutions, and collecting proposed solutions. This research process inherently led to the identification of stakeholders and their needs. Over three weeks, stakeholders were tabulated, customer needs were listed, and engineering specifications were generated. Intermediate prioritization and reevaluation of these requirements occurred during this period as a concept of operations and functional analysis were developed. Customer attributes and system requirements were then analyzed in a House of Quality. Once specifications were solidified, the team began generating a multitude of concepts for consideration. In an iterative and scientific selection process, concepts were discussed and then eliminated, combined, or confirmed. Upon completion of concept ideation, at which a final system design was agreed, the team concurrently worked on technical risk and financial cost assessments. Throughout the latter half of the project, documents were prepared for submission in parallel with work on project content itself. These deadlines included:

- Project Update: November 11, 2019
- Project Presentation: December 5, 2019
- Project Report: December 9, 2019

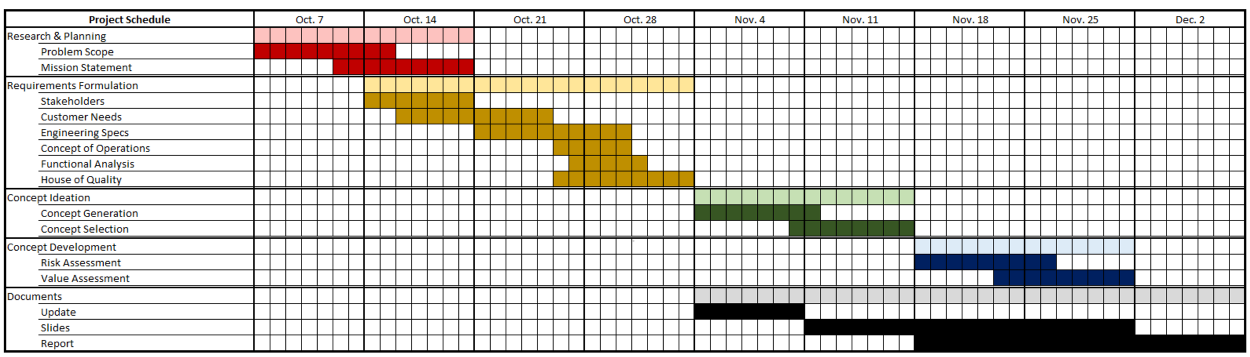

Figure 1: Gantt Chart Showing Expected Schedule

1.5 Assumptions

Core assumptions driving project design revolve around system operation and integration. First, it is presumed that this stage of drone delivery is intended to serve business-to-consumer (B2C) rather than business-to-business (B2B) deliveries across the last-mile; this is the focus of current industry experiment funding as order fulfillments to households are the most susceptible to unpredictability in delivery demand and route variation. By specification of ‘drone’ as the subject delivery vehicle, the desired solution is assumed to be unpiloted and untethered. Human interactions with the drone are also assumed necessary for package onloading and offloading, though this may be electronic via software rather than mechanical. Central to the integration of the drone delivery system into the network of a package carrier, it is presumed that package and destination assignment algorithms that optimize the system’s utility within an overall logistics infrastructure are developed and modified by the cargo transportation company itself. As a result, the drone delivery system as proposed and evaluated in this project consists of flight vehicle hardware and guidance, navigation, and control software.

2. Requirements Analysis

2.1 Stakeholder Identification

Identifying the stakeholders is drives all subsequent design and requirement choices, and was thus a paramount, initial task. All stakeholders were classified into five major categories by organizational structure and purpose. These five categories of stakeholders in a package delivery system are: delivery operators, such as FedEx, Amazon, UPS and USPS; regulators of air space such as FAA, local authorities and airports; other users of the airspace, such as airlines, military and general population; delivery system manufactures, such as Blade and Parrot; and the retailers and customers of shipped goods.

2.2 Needs and Prioritization

From the list of stakeholders, a requirements list is generated to meet each customer's need. The table below shows the needs generated by the team.

Group	Rank	Need
Operators	8	Drone shall transport cargo faster than ground shipping.
	7	Drone shall transport cargo cheaper than ground shipping.
	9	Drone shall provide the range to bridge the last-mile gap.
	11	Drone shall carry multiple medium-sized packages.
	19	Drone shall efficiently plan and navigate delivery routes.
	10	Drone shall detect and avoid obstacles in its course.
	23	Drone shall operate normally in mild precipitation and winds.
	25	Drone shall operate normally in reduced visibility environments.
	24	Drone shall operate normally after repeated hard landings.
	13	Drone shall offer a remote piloting capability.
	12	Drone shall regularly transmit tracking data to a control center.
Producers & Consumers	14	Drone shall be securely and expediently unloaded.
	15	Drone shall deliver its payload in a safe and convenient location.
	21	Drone shall insulate its payload from weather conditions.
	20	Drone shall protect its payload from excessive loading.
	22	Drone shall notify customers of impending deliveries.

Group	Rank	Need
Regulators	30	Drone shall limit its noise, light, and air pollution.
	27	Drone shall avoid harming wildlife in the sky or ground.
	5	Drone shall avoid flying within restricted airspace.
	1	Drone shall comply with FAA Part 135 regulations.
	2	Drone shall comply with NextGen ATC LAANC regulations.
	3	Drone shall yield to commands from authorities.
	4	Drone shall avoid contacting nearby persons or structures.
	6	Drone shall notify other airspace users of its presence.
Manufacturers	18	Drone shall protect itself from criminal activities.
	17	Drone shall limit maintenance downtime.
	26	Drone shall limit its power draw.
	28	Drone shall prevent cargo movement.
	16	Drone shall be easily serviceable and reliable.
	29	Drone shall store performance data for evaluation.

Figure 2: Requirements

To prioritize the requirements, the team decided to use a simple 1-3-9 ranking with 1 being the most essential, 3 being a highly desired need and 9 being a non-essential or secondary need of the system. This generated a list that was later added to the House of Quality to be analyzed with the engineering requirements.

2.3 Engineering Specification

To balance the large amount of needs with operational and environmental constrains, qualitative needs were correlated with quantitative system metrics. Assessing system effectiveness in satisfying stakeholder needs, metrics were given marginal and ideal value thresholds for the designed system. Target values were chosen through research on the performance of competing drone delivery systems and current ground delivery platforms. For example, desired payload weight of 10 lbs. and volume of 2016 cu in. were set to hold two of Amazon's 'standard' package sizes; 86% of Amazon packages are within these constraints [3].

Weight	Specification	Marginal Value	Target Value
.15	Drone delivery cost ($/mi.)	$3.00/mi	$2.50/mi
.1	Drone cruise speed (mph)	50	60
.1	Drone delivery range (mi.)	20	30
.02	Drone flight endurance (hr)	1 hr	1.25 hr
.02	Drone flight ceiling (ft)	500 ft	750 ft
.05	Drone navigational positioning error (ft)	5 ft	1 ft
.02	Drone power draw (Ah)	20 Ah	15 Ah
.03	Obstacle detection distance (ft)	400 ft	500 ft
.05	Obstacle separation distance (ft)	100 ft	150 ft
.01	Tolerable wind speed (mph)	15 mph	25 mph
.01	Drone system annual loss rate (%/year)	5%	2%
.01	Drone system mean time to failure (years)	5 years	10 years
.03	System mtc to ops time ratio (#)	.1	.05
.01	Drone light pollution (lumens)	1200 lum	1000 lum
.01	Drone noise pollution (decibels)	90 dB	50 dB
	Vehicle Performance		
.1	Payload size (cu in.)	2016 cu in	3024 cu in
.1	Payload weight (lbs)	10 lbs	12 lbs
.03	Payload on/off-loading time (sec)	90 sec	60 sec
.02	Payload on/off-loading steps (#)	5 steps	3 steps
.03	Payload acceleration exposure (Gs)	3 Gs	2 Gs
.05	Payload delivery location error (ft)	10 ft	5 ft
.01	Datalink bandwidth capacity (Mbps)	5 Mbps	10 Mbps
.01	Datalink latency time (sec)	2 sec	1 sec
	Payload Delivery		

Figure 3: Selected Requirements

Requirements are ranked in importance from 1-10 with 10 being essential to system performance and 1 meaning an unnecessary nicety. Weights are normalized for entry into concept selection matrices. The most important specifications were determined to be payload size and weight, drone speed and range, and obstacle avoidance capabilities. However complex in intricate interdependencies and overall performance, these requirements are all secondary to compliance with Federal Aviation Administration regulations.

2.4 Functional Analysis

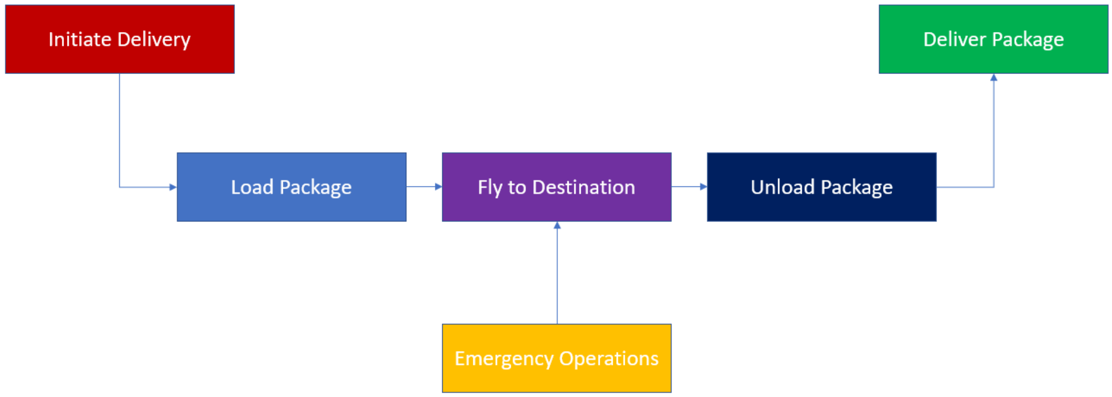

Figure 4: System Functional Analysis Overview

Team 19 decided to break down the components of the entire delivery operation so as to come up with various concepts which meet each functional requirement for the system. The delivery process was broken down into 5 functions with 3 vital function in between “Initiate Delivery” and “Deliver Package”. These three functions will be further explained in the next few pages of the report. It was also determined that the DS could only encounter emergency situations during the flight phase of the delivery as it would be in the control center during all other phases of the mission. Thus, another sub-function that only affects the flight phase was added, titled “Emergency Operations”.

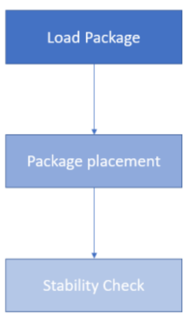

Figure 5: Load Package Function

The Load Package function was determined to only require 2 sub-functions. One would address loading of the package. The other would test the package for secure placement and impact on safe flight. This would ensure the same quality and flight performance for all deliveries.

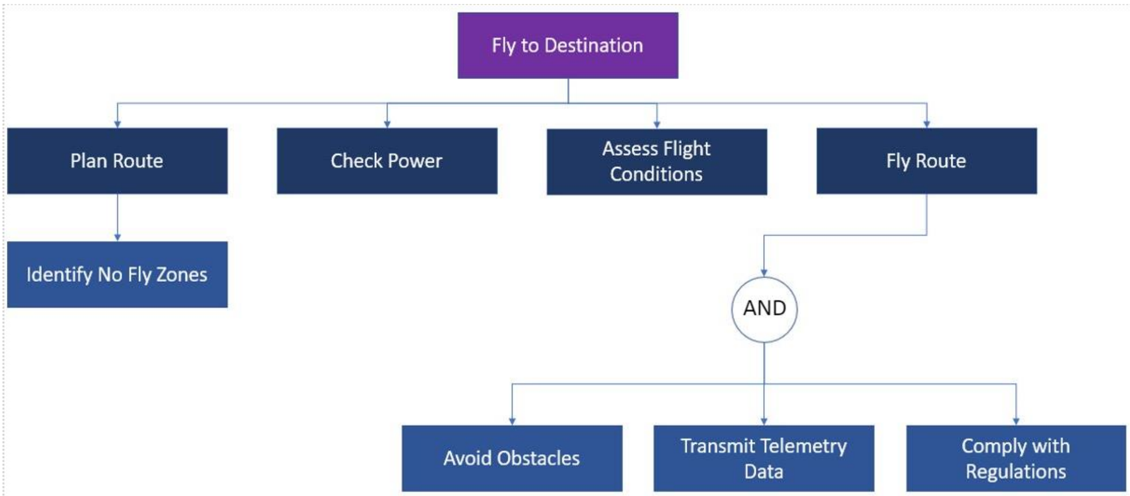

Figure 6: Fly to Destination Function

For the Fly to Destination function, the team decided that the DS would plan an optimal route before taking off from the operations center. This route would identify and avoid no fly zones. The DS would also check to make sure that the batteries have enough charge for a round trip, with 15% extra charge in case of emergencies. Finally, it would assess environmental conditions for an effect on its flight capabilities. While it was en-route, it would avoid all obstacles such as buildings, birds, trees and other aircraft while transmitting its telemetry data to the operations center and complying with all FAA Part 135 regulations.

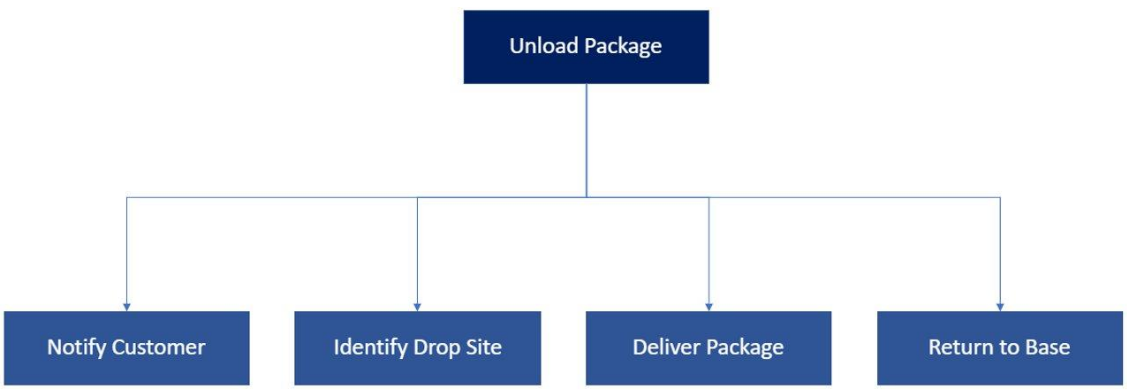

Figure 7: Unload Package Function

The Unload Package function would consist of 4 phases. The DS would notify the customer of an upcoming delivery prior to reaching the destination. It would then identify a safe drop site where it could deliver the package. This site would have to be clear of obstacles that could hinder delivery and clear of animals and humans so as to not injure them during delivery. The DS would then drop off the package to its destination and return to base while simultaneously informing the Operations Center of a successful delivery.

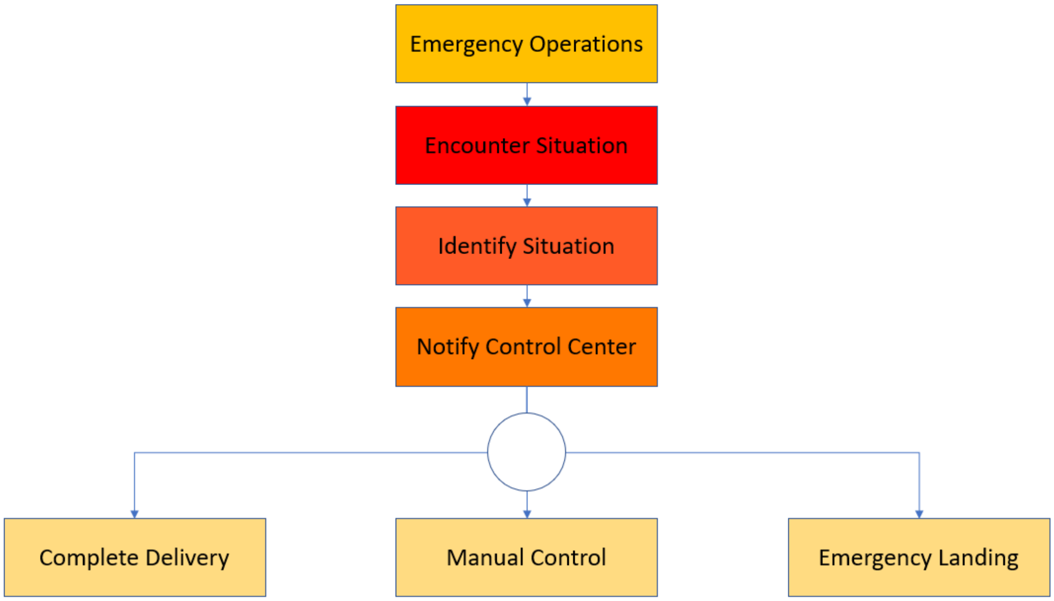

Figure 8: Emergency Operations Function

The Emergency Operations function is vital to ensure that the DS is well equipped to deal with any obstacles it could encounter during delivery which could either hinder delivery or pose a risk to customers. If the DS were to encounter a situation during flight, it would first attempt to identify the situation so that the control center would be able to respond appropriately. The controller would then select one of three options: command the DS to complete delivery autonomously, take manual control of the DS, or command the DS to perform an emergency landing.

2.5 House of Quality

The House of Quality (HoQ) is a design tool that allows for deeper analysis of the importance of each technical requirement with respect to the customer needs. The HoQ aids in prioritizing and rewriting specifications before the concept generation and selection process. Due to the size of the HoQ created by Team 19, a condensed version is presented in Figure 9 which includes five most important requirements. The team found that complying with regulations, minimizing power draw, and having enough range to perform all operations were the top three requirements with respect to meeting customer needs. Figure 10 shows a screenshot of the full HoQ, and Figure 11 shows the "roof" of the HoQ. As the HoQ is difficult to read, a link to a full-size version is included in the appendix under

	Project:	Last Mile Drone Delivery - Team 19					
	Date:	11/3/2019					
		Team 19's Quality House of Quality					
		Direction of Improvement	□	▼	▲	▲	▼
Ranking	Normalized Weight	Customer Requirements	Compliance with FAA LAANC ATC directives	Fleet Loss Rate	Distance from obstacles during cruise flight	Distance from obstacles during terminal flight	Maximum power draw
10	6%	Delivers packages at a faster speed than ground shipping	0	0	0	0	-2
10	6%	Delivers packages at a cheaper cost than ground shipping	0	2	0	0	0
6	3%	Can be loaded and unloaded in a secure yet expedient manner.	0	0	0	0	0
5	3%	Identifies landing sites so that packages are delivered in convenient and safe locations.	0	0	0	0	-1
3	2%	Operates normally after repeated hard landings.	0	0	0	0	0
6	3%	Can hold and lift multiple medium-sized packages.	0	0	0	0	-1
5	3%	Insulates its cargo from weather conditions.	0	0	0	0	0
2	1%	Limits its inertial acceleration as to reduce applied stresses on itself and its cargo.	0	0	1	1	1
9	5%	Can takeoff and land vertically, and hover in place.	0	0	0	0	-2
10	6%	Does not collide with terrain, buildings, wildlife, or people.	2	-2	2	2	0
10	6%	Regularly transmits its position, speed, and heading to air traffic control centers and company network operations centers.	2	0	0	0	-1
4	2%	Can be tracked by consumers and producers of delivered goods via mobile and desktop applications; real-time requests from distributors or customers can reroute, delay, cancel, or expedite the DS.	1	0	0	0	-1
7	4%	Automatically generates a safe and quick route for delivery and autonomously navigates along the route from pick-up to drop-off.	1	0	2	2	0
6	3%	Navigates efficiently between distribution centers and homes or offices.	0	0	-1	0	0
1	1%	Limits its noise, air, and light pollution during flight.	0	0	1	1	0
10	6%	Cruises above natural and artificial terrain yet avoids restricted airspaces.	2	1	2	2	-1
4	2%	Requires minimal maintenance and charging downtime	0	1	0	0	1
9	5%	Protects its internal power supply from external damage due to weather or stresses.	1	0	2	2	0
8	4%	Has the range to bridge the last mile gap between distribution centers and consumer households.	1	0	0	0	-1
1	1%	differentiates between packages as to pick up and drop off the correct package.	0	0	0	0	0
6	3%	Protects itself and its cargo from criminal activities, such as hacking, vandalism, or theft.	0	2	0	1	0
7	4%	Operates normally in mild precipitation and winds; quickly and safely returns to base during severe weather conditions.	0	1	1	0	-1
4	2%	Operates normally overnight and in other reduced visibility environments.	0	0	1	0	0
4	2%	Avoids harming animals and refrains from crashing after suffering a bird strike.	1	2	1	1	0
8	4%	Can be interfaced, stopped, and deactivated by police and rescue authorities.	2	1	0	0	0
10	6%	Retains the option to be piloted by a remote, manual operator.	1	0	0	0	0
3	2%	Collects, stores, and analyzes telemetry and delivery data; this information can be accessed remotely.	0	0	0	0	-1
7	4%	Is visible during the day and night to individuals on the ground.	0	0	0	0	-1
3	2%	Can be interfaced by individuals with visual or auditory disabilities.	0	0	0	0	0
178	1	Absolute Value Sums	14	12	14	12	15
		Sums	14	8	12	12	-11
		Importance Rating Sum (Importance x Relationship)	0.662921348	0.5	0.539325843	0.47752809	0.584269663
		Relative Weight	1	4	3	5	2

Figure 9: House of Quality Top Five

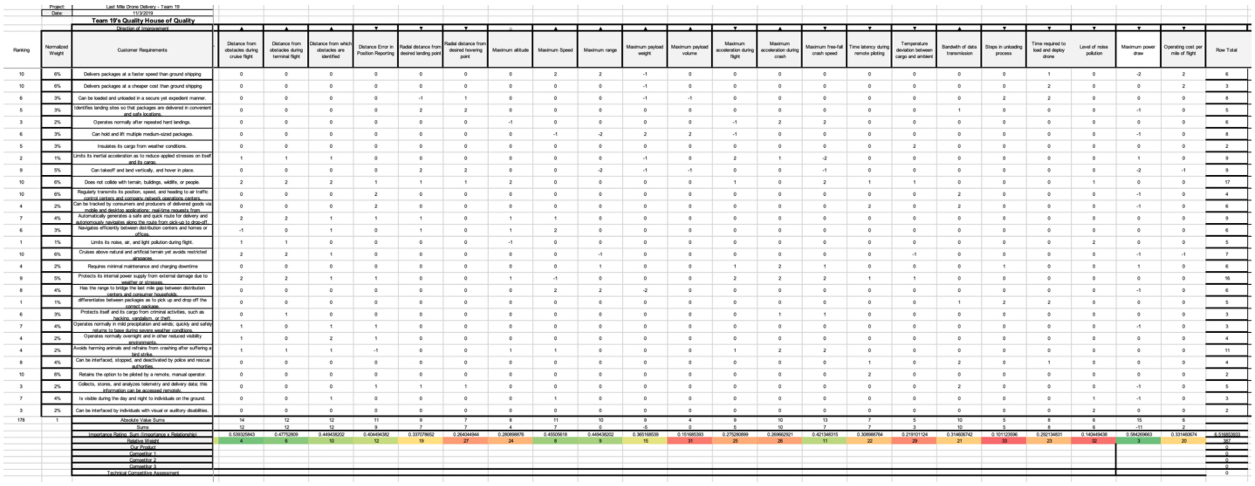

Figure 10: Full HOQ

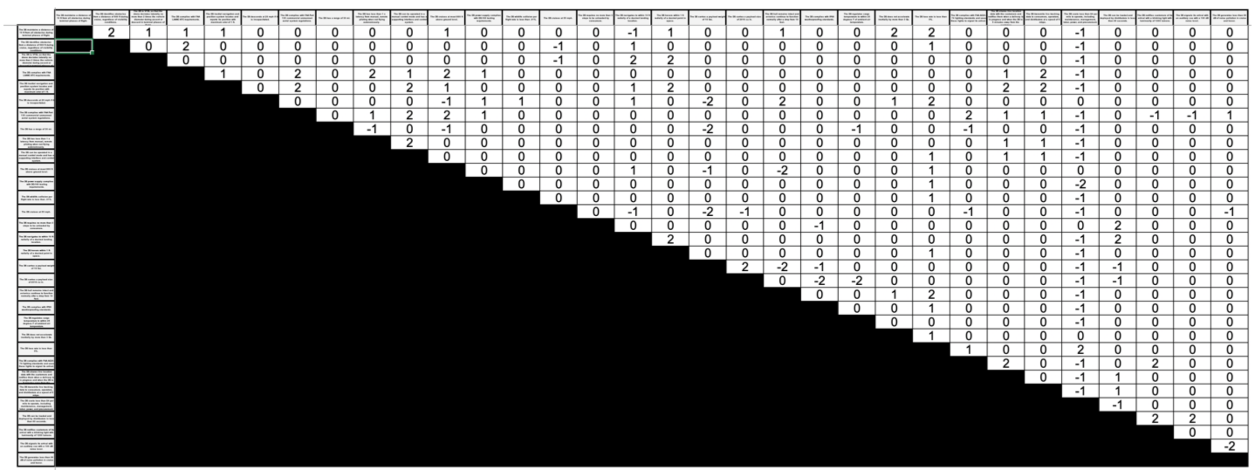

Figure 11: HOQ Roof

3. Initial Concepts

3.1 Concept Generation

Team 19 used a concept generation table, shown in *Figure 12,* as well as a review of existing designs to create concepts to consider. Overall, eleven concepts were considered.

Propulsion	**Power**	**Cargo**	**Notification**	**Battery**
Jet	Solar	Bag	Horn	LiPo
Rocket	Battery	Box	Blinker	LiHV
Single Rotor	Nuclear	Claws	App	NiMH
Coaxial Rotors	Jet	Rope		NiCd
Quadcopter		Internal Bay		
Hexacopter				
Octocopter				

Figure 12: Concept Combination Table

Multicopters have the advantage of redundancy against motor failure and higher thrust from multiple rotors. They are speed limited by drag and configuration.

The forward and vertical props concept was inspired by Alphabet’s Wing design, shown in Figure 13. This concept provides vertical/short takeoff and landing capabilities (V/STOL), while also giving a higher top speed and better efficiency in forward flight.

Figure 13: Alphabet Project Wing

The tiltrotor concept was inspired by the FireFly6 drone, shown in Figure 14 as well as military tiltrotors such as the V-22 Osprey. Tiltrotors, like the forward and vertical props design, have the V/STOL advantages of a multicopter with the forward flight speed and efficiency of a fixed wing aircraft. Unlike the forward and vertical props design, the same rotors are used for vertical and forward flight. This leads to more complexity in the control scheme but can yield a weight reduction compared to the forward and vertical props design.

Figure 14: FireFly Tiltrotor Drone

The catapulted fixed wing concept was based on the C-Astral BRAMOR, shown in Figure 15. The key feature of this design is a catapult-assisted takeoff which would reduce power needed for takeoff and increase range. Aside from this, the design is a simple fixed wing design. Thus, it would be efficient and fast in forward flight, but would lack V/STOL capabilities necessary for delivery and landing without runways.

Figure 15: Catapulted C-Astral BRAMOR

The helicopter concept was a simple, single main rotor helicopter with a tail rotor. This design is well-proven. Building on this concept, a coaxial with pusher configuration was considered, shown in Figure 17. This design has been used effectively by Sikorsky on its X-2 and S-97 models. Both of these helicopters are able to fly much faster than conventional helicopters. In this way, they combine the speed advantage of a fixed wing aircraft with the V/STOL capabilities of a helicopter.

Figure 16: Sikorsky X-2 Coaxial Pusher Configuration

A modular multicopter concept, based on the Altinay Albatross, shown in Figure 17 was also considered. This concept would be able to carry a variety of payload pods underneath, and the number or rotors would be adjustable for different cargo sizes. The advantage of this design over a standard multicopter is adaptability for different cargo missions. Designs could be configured to prioritize range, cargo size, or other factors.

Figure 17: Altinay Albatross Modular Multicopter

A few less conventional concepts were considered. One was an unmanned blimp. Blimps are extremely efficient as they expend no energy to stay airborne. They are also capable of V/STOL and are a proven, reliable design. However, they are very large for the amount of cargo they carry and are difficult to control in bad weather.

Rocket powered, guided, ballistic delivery vehicles were also considered. These would be much faster than any other delivery method. They would also be capable of vertical takeoff. However, they would be the most unsafe and unpractical method of delivery. Reusing these vehicles would be difficult, unless they could land and take off during the mission. FAA approval would be very unlikely.

Finally, Santa Clause and his sleigh were considered as a delivery method. Santa is able to deliver about 7 billion packages in one night, so rapid delivery is not an issue. He is able to land on rooftops, so delivery capability is not an issue either.

For the second iteration of concept generation, a new concept was created by combining the multicopter and fixed wing elements to form a tail sitter concept, shown in Figure 18. This design can hover and is capable of V/STOL but can also fly forward. This concept combines the advantages of a multicopter with the advantages of a fixed wing aircraft. It is also lighter than both the forward and vertical props concept and the tiltrotor concept. Like the tiltrotor, it would be complex to control.

Figure 18: Prime Air Tailsitter

In addition to choosing a concept for the overall configuration, a delivery method needed to be chosen. Landing and releasing the package was an obvious option. However, this option increases the risk that a person or animal is hurt or damages the drone.

Lowering the package on a tether eliminates the need for the drone to land, while setting the package down gently. This eliminates the risk that humans or animals will contact the drone. It also introduces another risk if the tether is severed prematurely.

A parachute is a third option for delivery. This method doesn’t require the drone to stop and hover, opening this as an option with concepts which do not have V/STOL capability. However, the parachute is less controllable than a tether or landing. In addition, parachutes can fail if not packed properly. Ultimately, the parachute would either need to be collected for reuse or discarded.

A robotic arm and claw system is yet another delivery option. This option offers the greatest accuracy and limits the risk of people or animals contacting the drone. However, it increases weight and complexity, as well as adding failure modes to the delivery system.

It is possible to drop the packages from the drone at a reduced altitude. This is the simplest method of delivery; however, it poses a risk of harming merchandise or people on the ground.

A glider can also be used to deliver cargo. This is one of the more complex options. The glider would not necessitate V/STOL, since it would be dropped by an aircraft in forward flight. The glider would either need to incorporate a built-in guidance system or would suffer from reduced accuracy. Gliders would need to be collected after delivery, mandating another trip by a ground vehicle.

Finally, a rocket booster could be used to land the package on the ground. This approach adds weight, complexity, and failure modes. Like the rocket powered, guided, ballistic delivery concept, this approach would likely prove too dangerous to consider.

3.2 Concept Selection

In order to narrow down the concept choices, a modified concept generation matrix was used (Figure 19-Figure 22. Each concept was input into the matrix. The multicopter was chosen as the baseline design, as it is a commonly used design for drones. From this baseline, all other designs were given a comparative rating of 1: better, 0: equal, or -1: worse in 8 categories. Comparative rankings were determined through consensus by the team.

Criteria	Baseline Multicopter	Forward & Vertical Props	Tiltrotor	Plane Catapult	Modular Multicopter	Traditional Helicopter	Coaxial Rotors & Push Prop	Rocket	Santa	Blimp
Speed	0	1	1	1	0	0	1	1	1	-1
Cost	0	-1	-1	1	-1	-1	-1	-1	-1	-1
Range	0	1	1	1	0	-1	-1	1	1	1
Safety	0	1	-1	-1	-1	0	0	-1	1	-1
Durability	0	-1	-1	0	1	1	-1	-1	1	-1
Delivery Capability	0	0	0	-1	0	0	0	-1	1	-1
Payload Capacity	0	1	0	1	1	-1	-1	1	1	1
Maneuverability	0	1	-1	-1	0	-1	-1	-1	-1	-1
Score	0	3	-2	1	0	-3	-4	-2	4	-4
Rank	4	2	6	3	4	8	9	6	1	9
Continue?	Yes	Yes	Yes	Yes	Yes	No	No	No	Busy	No

Figure 19: General Configuration Selection Iteration One

The top 5 designs were chosen to move on to the next iteration of concept generation. As there was a tie between the tiltrotor and rocket, a qualitative decision was made to eliminate the rocket. The anticipated danger and complexity involved in a rocket propelled system discouraged the team from using this design. In addition, the potential delivery speed benefit was not compelling enough to outweigh the foreseen risks. Finally, the configuration was dissimilar to the other configurations and would require more development. The traditional helicopter, coaxial rotor helicopter, guided ballistic delivery system, and blimp were all eliminated. Santa was unavailable for use. Fourth, the forward and vertical props design has the potential to carry more cargo than

In the second round of concept selection, the five best concepts from iteration one, plus the new concept were put in a new matrix (Figure 20). In this round, each criterion was given a weight to help differentiate between concepts. Each criterion was given a ranking from one to five, with one being least important and five being most important. These scores were then normalized to add up to one. Safety was most important. Cost and delivery capability were made second most important. A system that can't deliver properly is useless. Prohibitively high costs would also kill the project. Range and speed are key performance factors and were next highest.

Maneuverability was considered least important. As in the first matrix, rankings for each design were determined by team consensus.

Criteria	Weight	Multicopter	Forward & Vertical Props	Tiltrotor	Plane Catapult	Modular Multicopter	Tailsitter
Speed	0.13	2	4	5	5	1	3
Cost	0.17	4	2	1	2	2	3
Range	0.13	3	4	4	5	3	4
Safety	0.21	4	5	2	3	3	2
Durability	0.08	3	2	1	3	4	3
Delivery Capability	0.17	4	4	4	1	4	3
Payload Capacity	0.08	3	4	4	5	4	3
Maneuverability	0.04	4	5	3	2	4	1
Score		3.46	3.75	2.92	3.13	2.96	2.83
Rank		2	1	5	3	4	6
Continue?		No	Yes	No	No	No	No

Figure 20: General Configuration Selection Iteration Two

This matrix projected the forward and vertical props design as the best design, with the multicopter placing second by 0.29 points. The narrow lead of the forward and vertical props design meant that the results of the selection matrix needed additional consideration. Essentially, the winning configuration could not necessarily be declared a clear winner. The forward and vertical props design was chosen for a few reasons. First, it has a safety advantage over the multicopter. Since the forward and vertical props configuration includes a wing and operates like a fixed wing aircraft for most of its flight, it has an extra factor of safety over a multicopter. If the forward and vertical props configuration has an engine failure, it is able to glide to a landing. The multicopter is much more likely to endanger people and property in an engine failure. Second, the forward and vertical props design has a much higher theoretical top speed than the multicopter. This means it would be able to far exceed the given speed requirement and deliver packages far faster than ground vehicles. While the multicopter would be able to meet the speed requirement, any additional speed would increase the benefit of the new delivery system over current ground systems. Third, the wing on the forward and vertical props design means the design can operate more efficiently in forward flight than a multicopter can. This would translate to a range and efficiency increase. Increased range means a larger area that can be served. Increased efficiency means a smaller environmental footprint and lower operating costs compared to alternatives. The only area where the multicopter has an advantage over the forward and vertical props configuration is in cost. As seen in section 4.2 Value Assessment, the forward and vertical props configuration is still able to profit. In addition, the number and importance of the advantages were deemed to be worth the increased cost.

The chosen concept provided a good combination of range and speed in forward flight and ability to deliver via V/STOL capability. The concept was considered to be ideal for a high payload capacity.

To select a delivery method, the same two-iteration approach was repeated. Landing was selected as the baseline design in both iterations, as it is the most obvious solution. As in the first iteration of the general configuration matrix, each concept was given a 1, 0, or -1 in relation to the baseline by team consensus. The concepts were graded in eight criteria. The results of the first iteration are shown in Figure 21.

Criteria	Baseline Landing	Drop	Parachute	Tether	Glider	Booster	Robotic Arm & Claw
Speed	0	1	1	1	1	1	-1
Cost	0	1	1	1	-1	-1	-1
Safety	0	-1	-1	1	-1	-1	1
Power	0	1	1	-1	1	-1	-1
Payload Weight	0	-1	-1	1	-1	-1	-1
Payload Size	0	-1	1	-1	-1	-1	-1
Delivery Accuracy	0	-1	-1	-1	-1	-1	1
Delivery Convenience	0	-1	-1	0	-1	-1	-1
Score	0	-2	0	1	-4	-6	-3
Rank	2	4	2	1	6	7	5
Continue?	Yes	Yes	Yes	Yes	No	No	No

Figure 21: Delivery Method Selection Iteration One

After the first iteration, the robotic arm and claw, glider, and booster concepts were eliminated. Each of these concepts proved to have comparatively bad performance. This made qualitative sense to the team.

For the second iteration, each criterion was weighted. Again, safety was given top priority, shared with delivery accuracy. Accuracy is key as it ensures packages aren't delivered to the wrong address. Speed was deemed next most important, as it increases delivery efficiency, followed by payload weight able to be delivered and delivery convenience. The second iteration matrix is shown in Figure 22.

Criteria	Weight	Landing	Drop	Parachute	Tether
Speed	0.17	1	4	3	2
Cost	0.04	2	4	1	3
Safety	0.21	2	1	3	4
Power	0.04	1	3	4	2
Payload Weight	0.13	3	2	1	4
Payload Size	0.08	3	2	1	4
Delivery Accuracy	0.21	4	1	2	3
Delivery Convenience	0.13	4	1	2	3
Score		2.67	1.92	2.21	3.21
Rank		2	4	3	1
Continue?		No	No	No	Yes

Figure 22: Delivery Method Selection Iteration Two

From the second iteration of delivery selection, the tether was determined to be best, followed by landing. Tethering avoids many of the risks of landing by allowing the drone to hover at a safe altitude above the drop location. Dropping the package poses too many risks, and using a parachute is too complex and inaccurate.

The final concept following general configuration selection and delivery method selection is shown in Figure 23. This design features vertical rotors to give it a V/STOL capability, fixed wings and a propeller for forward flight, and recessed package storage. At the delivery location, the package is lowered on a tether. The final concept is discussed in detail in Section 2.5.

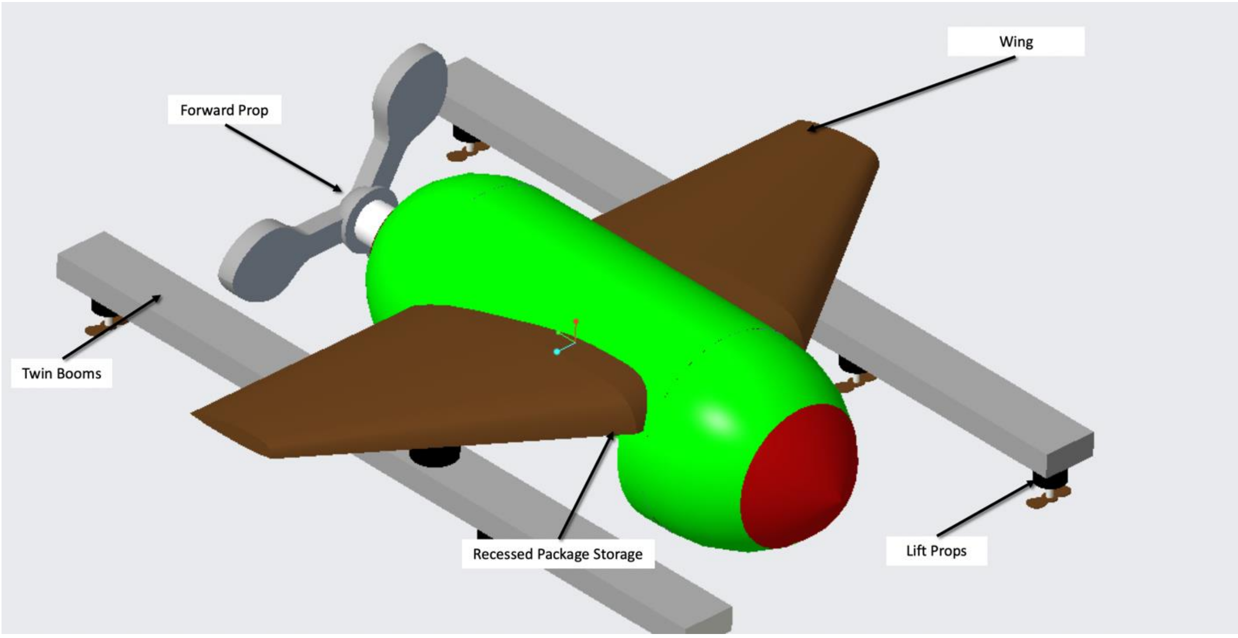

Figure 23: Final Concept

4. Concept Development

4.1 Risk Assessment

With this final concept created, Team 19 analyzed potential risks and failures for the delivery system. Two methods were used for this assessment: a FMECA and a Fault Tree Analysis.

The full FMECA is shown in the appendix, with the highest risk failure modes shown in Figure 24 and Figure 25.

The full Fault Tree Analysis is linked in the appendix in section Link to Fault Tree as it was too large to fit in this document. A screenshot of the Fault Tree is attached in Figure 26.

For the FMECA, key subsystems were identified, including the flight control system, the power system, the package carriage and delivery systems, and major structural components. The major failure modes of each system were identified. The likelihood of each failure mode occurring was scored, with 1 being very unlikely and 5 being extremely likely. These scores were placed in the Risk Level column. In addition, the severity of each failure mode was scored, with 1 representing delivery still possible and 5 meaning loss of the airframe. These scores were placed in the Severity column. For the benefit of the team, these scores were multiplied for each failure mode to generate a "Risk Score." In addition, for each failure mode, detection, compensation, effects, and preventative measures were investigated. Most modes are detectable via inspection and/or testing of aircraft components. Some failures are detectable in flight through the use of sensors, including a power system failure or a rotor failure.

For the Fault Tree, Team 19 identified 2 main systems that could cause a delivery to fail, Payload Failure and Vehicle Failure. Under Payload Failure, we considered failures stemming from the payload delivery system, since this is the only subsystem that interacts with the payload itself. Within this subsystem, we considered individual components and reached our basic events with individual component failures. The other main branch is the vehicle failure branch. This branch entails every type of failure related to the delivery drone itself. Therefore, the sub branches right below are the failure of individual design groups, like controls, propulsion, logistics, and structures. For logistics, Team 19 identified the most prevalent failure types as wrong payloads delivered and delivery to wrong addresses, and reached the basic events with this.

Under the structures group, the roots of structural failure were categorized as internal and external forces. The main internal force that can break the drone is the thrust and angular momentum generated by the engines, which is a basic event. However, for external forces, the mains causes could be aerodynamic forces or forces stemming from hitting objects/obstacles.

For the controls group, both electronical and navigational failures were considered. Electronics failure in this case strictly means components failing from electrical forces and computation, such as voltage drops and software errors. Three types of failures were identified under electronics, namely battery voltage failure, sensor failure, and flight computer errors.

Navigational failures can only be attained by the failure of the GPS components and the failure of uplink connection, since in case only one fails, the other sub system could take over and finish delivery. Under electronics failure, battery voltage drop was the basic event. Sensor failures can be caused by the failure of any of the following sensors, altitude, ground proximity, or IMU. The flight computer failure could be caused by hardware software failures, but it has been concluded that these are too detailed to be evaluated in this tree and should be developed elsewhere.

For propulsion system failures, two sources were identified as motor or propeller failures. Both would result in the loss of thrust. Prop failures are rather easy, since the main reason is generally prop strikes (external forces). Motor failures on the other hand are a more complex issue. For DC motors the two main reasons generally are the end of usable life, or failure due to maintenance problems. Again, maintenance was seen as too broad to cover in this fault tree, and was transferred out to be developed elsewhere.

ID	Purpose	Failure Modes	Failure Mechanism	Failure Detection	Failure Compensation	Failure Effects	Risk Level (1-Low, 5-High)	Severity	Preventative Measures	Risk Score
Lifting Rotors	Vertical Takeoff/Hover	Broken Blade	Impact, overstress, fatigue	Flight control system	Redundancy, transition to gliding flight	Loss of lift in hover/vertical flight	3	4	Construct of sturdy material, frequent inspection	12
		Motor Failure	Temperature, contamination, over/under-supply of power, moisture, lack of lubrication	Flight control system	Redundancy, transition to gliding flight	Loss of lift in hover/vertical flight	3	4	Construct of sturdy material, frequent inspection	12
Control Surfaces		Failure of control surface actuator	Temperature, contamination, over/under-supply of power, moisture, lack of lubrication	Inspection/Testing	Usage of other control surfaces/lifting motors for flight control	Inability to control aircraft	2	5	Frequent Inspection, Use reliable motors	10
		Control surface binding	Lack of lubrication, warping of components	Inspection/Testing	Usage of other control surfaces/lifting motors for flight control	Inability to control aircraft	2	5	Testing in many conditions	10
Flight Control System		Control failure	Bad input from air data system	Air data system validation from redundant sensors	Redundancy, emergency landing	Loss of control	3	5	Frequent inspection of air data system	15
			Control software malfunction	Software testing and validation	Emergency landing	Loss of control	3	5	Extensive software validation	15

Figure 24: Selected High-Risk Failure Modes from FMECA

ID	Purpose	Failure Modes	Failure Mechanism	Failure Detection	Failure Compensation	Failure Effects	Risk Level (1-Low, 5-High)	Severity	Preventative Measures	Risk Score
Power System	Provide power to flight control system and propulsive sources	Battery Failure	Chemical, impact	Voltage Sensor, Inspection	Redundancy	Loss of power in all systems	2	5	Use a reliable battery, swap batteries often	10
		Power Distribution Failure	Wires severed	Voltage Sensors, Inspection	Redundancy	Loss of power in some or all systems	3	4	Frequent Inspection	12
Package Carrying System	Safely retain package, protect package from damage	Retention motor failure	Motor Failure	Inspection	Speed and Altitude Reduction, Emergency landing or return to base, redundancy	Uncommanded Release of Cargo	3	4	Frequent Inspection	12
Package Lowering Tether		Lowering Motor Failure	Temperature, contamination, over/under-supply of power, moisture, lack of lubrication	Inspection	Use of ratchet mechanism to retain package, emergency landing	Uncommanded release of cargo	3	4	Frequent Inspection, Use reliable motor	12
		Cable Ratchet Failure	Impact, overstress, fatigue	Inspection	Use of motor to secure package	Uncommanded release of cargo	3	4	Frequent Inspection	12

Figure 25: Selected High-Risk Failure Modes from FMECA, cont.

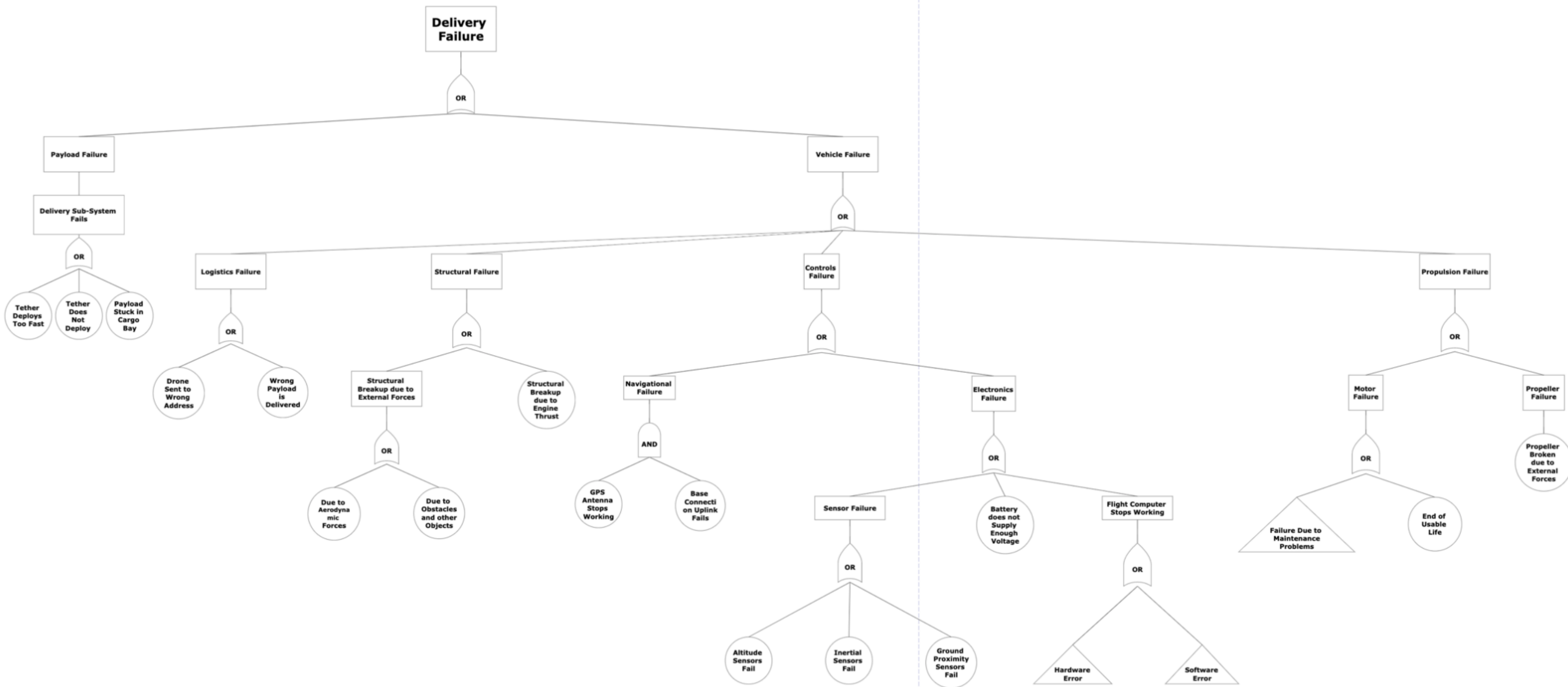

Figure 26: Fault Tree

4.2 Value Assessment

While the technical feasibility of a drone delivery system has been established, the financial viability of the shipping method must be further explored. A financial model of the costs and benefits expected from a drone delivery service was generated for three economic outlooks: pessimistic, optimistic, and realistic. Costs were assigned to three stages of a drone delivery program, development, procurement, and operation, with the latter including all support and maintenance expenses. As the baseline alternative to delivery by drone is that by truck, the system savings were estimated as to be the operational costs of ground shipping displaced by aerial shipping.

The model is driven by a table of numerical inputs for parameters relating to the efficiency and expense of operating both truck and drone delivery service. Values entered for each model variant were either calculated from available data, estimated through intuition and research, or taken from aforementioned system specifications; for example, salaries for delivery drivers, drone controllers, and shipping managers were found on wage aggregation sites while prices of utilities were found on federal cost-of-living databases, with both taken as averages for the State of Indiana.

Cost Center	Model			Units
	Pessimistic	Realistic	Optimistic	
Development				
Sensor Processing	2500	2000	1500	lines of code
Vehicle Control	6000	5000	4000	lines of code
Payload Weight	5	10	15	pounds
Empty Weight	12.5	25	37.5	pounds
Office Space	$ 1,500.00	$ 1,000.00	$ 500.00	($/month)
Engineer Wage	$ 10,000.00	$ 8,210.00	$ 7,500.00	($/month)
Procurement				
Materials	$ 12,000.00	$ 10,000.00	$ 7,500.00	($)
Assembly	$ 6,000.00	$ 5,000.00	$ 3,500.00	($)
Data Storage	$ 750.00	$ 500.00	$ 250.00	($)
Factory Space	$ 2,000.00	$ 1,500.00	$ 1,000.00	($)
Operation - Drone System				
Utility Rate	33%	35%	40%	(% flying time per day)
Loss Rate	10%	5%	3%	(% fleet lost per year)
Hazard Rate	5%	2%	1%	(% fleet broken per year)
Discount Rate	9%	10%	11%	(% financial return per year)
Speed	50	55	60	(mph)
Endurance	0.75	1	1.25	(hrs)
Power	0.6	0.5	0.4	(MW)
Electricity	$ 109.10	$ 104.50	$ 100.25	($/MWh)
Technician Wage	$ 33.92	$ 29.12	$ 26.90	($/hr)
Controller Wage	$ 44.58	$ 37.98	$ 34.62	($/hr)
Repair Factor	15%	10%	8%	(% of price per repair)
Data Link	$ 1.25	$ 1.00	$ 0.75	($/hour)
Operation - Truck Alternative				
Truck Economy	6	8	12	(mpg)
Truck Speed	25	35	50	(mph)
Truck Maintenance	$ 2.00	$ 1.75	$ 1.00	($/mi)
Gas Price	$ 3.43	$ 3.07	$ 2.66	($/gal)
Driver Wage	$ 31.43	$ 27.83	$ 17.92	($/hr)

Figure 27: Inputs to Financial Model

Logic of the model is split into computing financial estimates for system development and then system operation. Development costs are assessed through cost estimating relationships correlating lines of code and operating weights to software and hardware components, respectively. While the utilized cost estimating relationships were developed from data on military UAV programs, research yielded no other available, comparable, regressions.

The first cost estimating relationship appraises the number of engineer-months needed to write vehicle control and signal processing code, measured in the thousands of equivalent lines [6].

$$Staff\ (em) = 74.37 * VC^{1.71} + 3.15 * \ SP^{1.38}$$

The second cost estimating relationship appraises the component costs of an autonomous flight vehicle from its empty and payload weights, measured in standards pounds [7].

$$Cost\ (\$) = 8000 * PW + 1000 * EW$$

Realistic	Annually									
Object	Relationship				Costs			Year	Past Value	Present Value
	Coefficent	Exponent	Months	Engineers	Software	Hardware	Overhead			
VC Code	74.37	1.71	98.24	8.19	$ 806,587.99	$ 117,500.00	$ 98,244.58	(1.00)	$ 1,022,332.57	$ 1,124,565.82
SP Code	3.15	1.38								
Payload Weight	8,000	-								
Empty Weight	1,500	-								

Figure 28: Development Costs for ‘Realistic’ Model

An averaged computer science salary as well as estimated office overhead expense yielded development costs over $1 million for the system. Operations costs and savings were tabulated in a similar, though more complex, manner. The financial performance of the drone delivery system relative to truck shipping is projected for 15 years of future operation. First, the model computes the availability and usage of a drone, incorporating diminishing dispatch rates from assumed hazard and loss rates and technical performance from speed and range specifications. Time and distance of operation then yield approximated power, overhead, and repair costs; salaries for a program manager, drone controller, and system technician are similarly added. The model computes estimated savings by using system availability and usage to calculate the operational costs of ground shipping, broken between a driver, fuel, and truck maintenance, replaced by the drone’s operation. Cash flows are then annualized and discounted at a standard 10% rate to a year-zero datum. These flows may become negative in the advanced age of the drone delivery system; as drones age, fail and thus fly less, their per-mile profit margin over trucks is eroded by the costs of program overhead and repair. Years with negative cash flows are eliminated overall profitability calculations as it is assumed project management would end the program before expected returns become unsustainable.

Realistic		Daily									Annually	
Year	Performance		Costs					Savings			Future Value	Present Value
	Availability	Usage (mi.)	Power	Overhead	Manager	Repair	Mechanic	Fuel	Truck	Driver		
1	100%	462	$ 438.90	$ 8.40	$ 319.03	$ 285.60	$ 254.34	$ 177.29	$ 808.50	$ 367.36	$ 17,108.56	$ 15,553.24
2	97%	448	$ 425.38	$ 8.14	$ 309.20	$ 276.80	$ 251.11	$ 171.83	$ 783.59	$ 356.04	$ 14,901.97	$ 12,315.67
3	94%	434	$ 412.27	$ 7.89	$ 299.68	$ 268.27	$ 247.74	$ 166.54	$ 759.45	$ 345.07	$ 12,847.32	$ 9,652.38
4	91%	421	$ 399.57	$ 7.65	$ 290.44	$ 260.01	$ 244.26	$ 161.41	$ 736.05	$ 334.44	$ 10,935.76	$ 7,469.27
5	88%	408	$ 387.26	$ 7.41	$ 281.50	$ 252.00	$ 240.68	$ 156.43	$ 713.38	$ 324.13	$ 9,158.88	$ 5,686.94
6	86%	395	$ 375.33	$ 7.18	$ 272.82	$ 244.23	$ 237.02	$ 151.61	$ 691.40	$ 314.15	$ 7,508.74	$ 4,238.49
7	83%	383	$ 363.77	$ 6.96	$ 264.42	$ 236.71	$ 233.27	$ 146.94	$ 670.10	$ 304.47	$ 5,977.83	$ 3,067.57
8	80%	371	$ 352.56	$ 6.75	$ 256.27	$ 229.42	$ 229.47	$ 142.42	$ 649.45	$ 295.09	$ 4,559.07	$ 2,126.84
9	78%	360	$ 341.70	$ 6.54	$ 248.38	$ 222.35	$ 225.61	$ 138.03	$ 629.44	$ 286.00	$ 3,245.75	$ 1,376.52
10	75%	349	$ 331.17	$ 6.34	$ 240.72	$ 215.50	$ 221.72	$ 133.78	$ 610.05	$ 277.19	$ 2,031.54	$ 783.25
11	73%	338	$ 320.97	$ 6.14	$ 233.31	$ 208.86	$ 217.78	$ 129.65	$ 591.26	$ 268.65	$ 910.44	$ 319.10
12	71%	327	$ 311.08	$ 5.95	$ 226.12	$ 202.42	$ 213.83	$ 125.66	$ 573.04	$ 260.37	$ (123.19)	$ (39.25)
13	69%	317	$ 301.49	$ 5.77	$ 219.15	$ 196.19	$ 209.86	$ 121.79	$ 555.38	$ 252.35	$ (1,074.70)	$ (311.30)
14	67%	308	$ 292.21	$ 5.59	$ 212.40	$ 190.14	$ 205.88	$ 118.04	$ 538.27	$ 244.57	$ (1,949.13)	$ (513.27)
15	65%	298	$ 283.20	$ 5.42	$ 205.86	$ 184.29	$ 201.90	$ 114.40	$ 521.69	$ 237.04	$ (2,751.24)	$ (658.62)

Figure 29: Operations Costs for 'Realistic' Model

From variable drivers and coded logic, the model generates a table and graph of numerical outputs. Estimated procurement cost is subtracted from its projected operational profit of the drone delivery system to yield an approximate, per-unit return on investment, neglection development costs.

Summary	Pessimistic	Realistic	Optimistic	Year(s)
Development	$ 1,417,365.86	$ 1,124,565.82	$ 991,027.51	-1
Procurement	$ 20,750.00	$ 17,000.00	$ 12,250.00	0
Operation	$ 24,904.74	$ 62,589.28	$ 93,661.05	1-15
Net (per unit)	$ 4,154.74	$ 45,589.28	$ 81,411.05	

Figure 30: Outputs of Financial Model

Aggregated financial performance is visualized in a chart of discounted cash balances over time. Development costs are incurred over a relative year '-1', procurement is expensed over year zero, and savings are realized upon system implementation at year '1'. The graph plots expected program balance of all three economic outlooks for three trial sizes: 10, 100, or 1000 units. Note that this analysis estimates a break-even time of 2.5 years and cost-per-mile of $2.82 for the 1,000 unit, 'realistic' model variant. All forecasts for the 100- and 1000-unit trials have positive net present values, indicating a potential business opportunity.

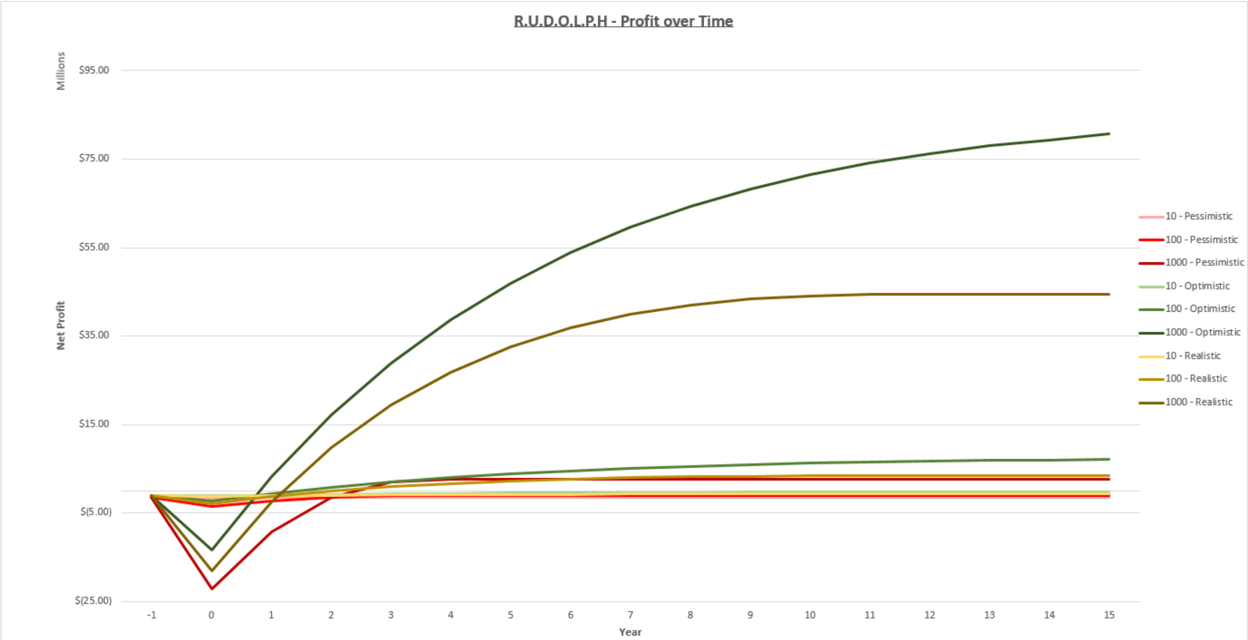

Figure 31: Aggregate Financial Performance

It must be noted that the financial model described herein is heavily limited by the validity of constituent driver estimates. At such an early stage of product development, there is relatively low confidence in the accuracy and precision of input parameters, and thus output values; significant regulatory and insurance costs are also omitted from analysis due to a lack of historical precedent. As a result, this model shall be considered a rudimentary framework with which a business case for adopting the drone system can be formed as technical development of the project progresses. Regardless, this thorough modelling of the costs and benefits of an aerial shipping system depicts realistically lucrative profit margins and supports the business case behind last-mile drone delivery.

4.3 Final Concept

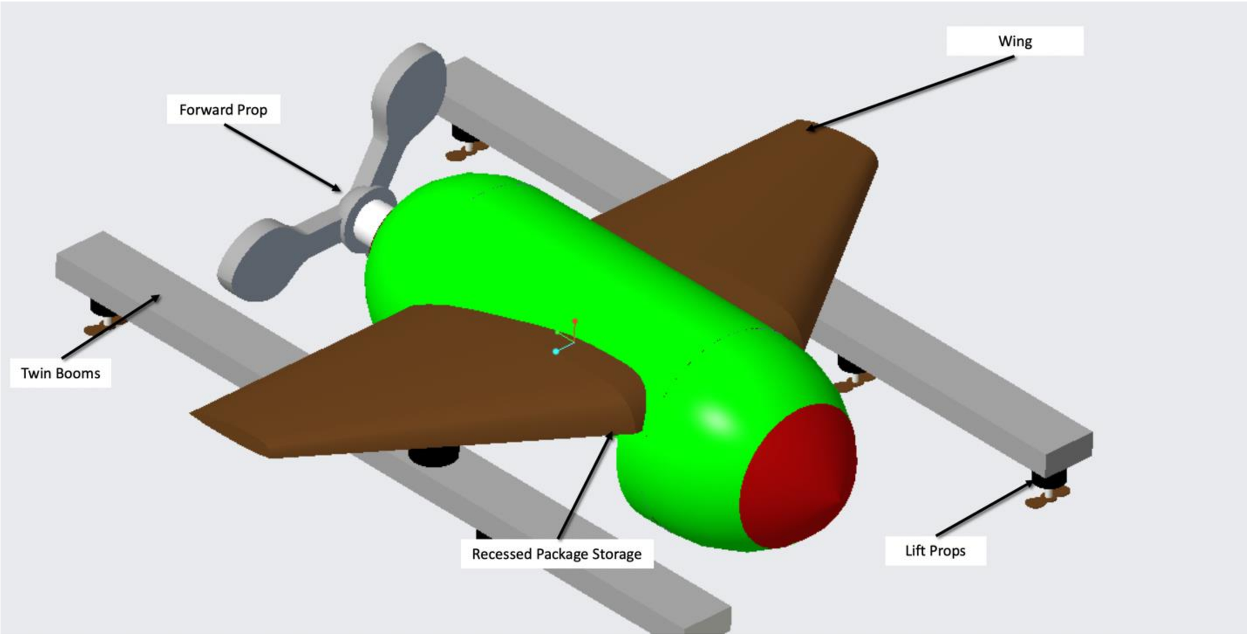

Figure 32: Final Design CAD Drawing

The final design can be seen in Figure 32. This CAD drawing shows the basic features of the product. Since this is only a conceptual drawing, information like length, height, diameters, wing area, and number of engines are still subject to change. The final design features are detailed below.

The drone will utilize wings as a way to generate lift, in addition to vertical engines. The wings will help us during the cruise phase of the flight by generating lift from the forward motion provided by the horizontal motors. By this, the main aim was to decrease the usage of motors, and thus decrease the need for battery capacity, which will enable the empty weight to be lower.

As mentioned in the paragraph above, the solution also utilizes a forward motor system to create horizontal thrust. This engine is comparatively bigger than the vertical engines (labeled as “Lift Props” in Figure 32). The forward engine will provide the horizontal speeds needed to generate enough lift for the wing. Overall, the goal is to have a longer range and a higher takeoff weight, while putting less strain on batteries.

Another thing to note in Figure 32 are the vertical engines. These engines will not only be used to take off, but they will also be used for stability and control of the plane. For example, the angle of attack could be changed by the usage of the fore-most and the aft-most engines, thus achieving pitch control. Roll control could be achieved by activating the engines on the port or starboard boom. Yaw control comes from the rotation direction of the vertical engines (CW or CCW) by the conservation of angular momentum, just like conventional multi-copters.

Structurally, two booms will support all of the vertical engines. The booms are attached to the underside of the wings using structural hardpoints. Unlike multi-copters, these booms are parallel to the direction of the flight, thereby decreasing drag and structural loads. This also leaves an open door for modularity to be included in the design. The booms can be extended, and more vertical engines could be attached to tailor the product for operator's needs, for example a larger payload delivery.

Lastly, the structure has a semi-external payload bay in the center. This provides more protection from elements compared with an external carriage, while also providing less drag and stability problems. The final design uses a tether to deliver payloads to desired destinations. There were two main reasons to use a tether to lower the payload. The first was customer safety. Since the drone will always be at a safe altitude while delivering the package, customers will be further away from the drone itself. This decreases the probability of a prop strike. The second reason is that almost every landing will be at a different place, so there are more variables that can affect safety, such as incline, vegetation, snow, or animals in the area. Not landing at all eliminates these risks.

4.4 Concept of Operations

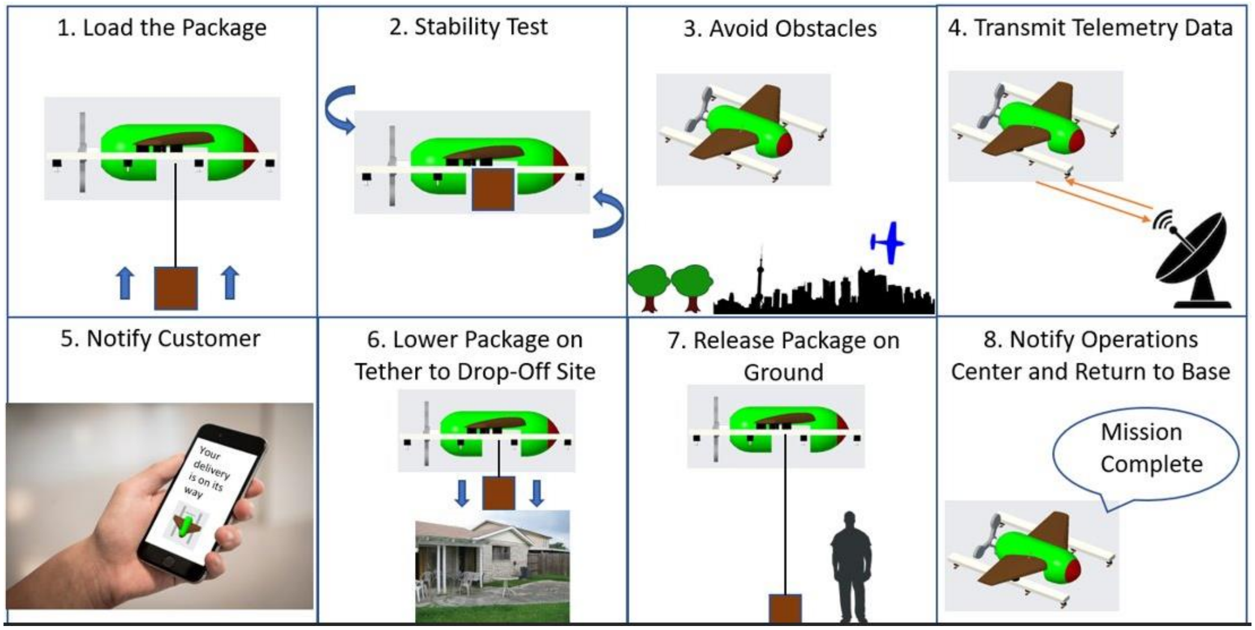

Figure 33: Concept of Operations

Team 19's ConOps helps to better understand how the final concept delivers packages by visualizing the whole process. The delivery process starts with Operations Center personnel loading the package onto the DS's tether and powering the DS on. The DS would then automatically roll the tether in, until the package is safely stowed into the open cargo bay. The DS would undergo a stability test to make sure that the package was secured and didn't affect flight performance before it was given clearance for takeoff. Right after takeoff, its main goal would be to avoid obstacles and no fly zones while constantly transmitting telemetry data back to the Operations Center. The Operations Center would store all the data from all parts of its flight and transmit the DS's live location to the customer through the delivery phone application. The Operations Center would automatically send a notification to the customer when the DS launches and when it is within 5 minutes from its destination. When the DS reaches its destination, it would start searching for a safe drop-off site and then lower the package onto the site using the tether. When the package makes contact with the ground, the DS would be able to sense the weight difference and release the package. It would then hover until the tether was fully loaded into the cargo bay and notify the Operations Center of a completed delivery and return back to its launch site for its next delivery.

5. Lessons Learned

The team learned and practiced the systems engineering principles within a formal design process. Since the project was partitioned into updates, we learned how to stick with the design process phase by phase. We also learned that this process is non-linear and highly iterative. For example, to come up with products, we evaluated existing concepts as well as generated our own. After this, we evaluated these concepts multiple times to eliminate weaker solutions.

Through a holistic and comprehensive approach to initial engineering design, the team developed greater awareness of the multidisciplinary skills behind product development, such as marketing, manufacturing, and financing. A structured design cycle also enhanced the team's proficiency in utilizing formal risk assessment and concept selection tools such as FMECA and Pugh matrices, respectively. This design project allowed the team to focus on the process of designing a system.

Through seeing presentations done by other teams and questions presented to our team, we learned to consider more solutions outside the box. For example, our team didn't consider ground-based solutions for last mile delivery. These would have been beneficial to consider during the concept creation and evaluation phase.

The team moved from a process of working on the project within team meetings to a more effective approach of dividing tasks to complete before each meeting which helped finishing tasks more efficiently as the team meetings were only held to get everyone up to speed and decide on what tasks the team had to do next.

6. Next Steps

Next steps of creating the solution would be performing more technical analysis on the chosen configuration. Details about the general configuration, such as sizes of the wings and rotors would need to be established. Thorough investigation of the certification requirements of unmanned delivery vehicles would need to be conducted to create a smooth and logical path to certification. Subsystems would need to be delegated to individual design teams. Software development of the control laws would need to start to allow time for thorough testing, especially in the current safety and certification climate.

While creating subsystems and sourcing components, failure rates could be investigated. During advanced subsystem design, more elaborate FMECAs and fault trees would be created. From these tools, failure rates of systems could be determined, as well as system lifetimes and maintenance intervals. These investigations would be key in validating subsystems and demonstrating compliance with FAA safety regulations.

After design of aircraft subsystems, testing and certification of subsystems could begin. Once systems were to a level of completeness to integrate, prototyping of full drones could begin. Following the construction of a prototype, an extensive testing program could begin to validate system performance and demonstrate compliance with regulations.

Throughout this process, design reviews by peers and experts would be necessary to ensure success. It is extremely important for fresh eyes to critique projects, to prevent a design team from overlooking design flaws. This could include additional peer reviews, reviews by management, reviews by technical experts, and reviews by engineers or regulators familiar with certification requirements and paths.

At the end of the certification process, the design would be marketed to potential customers. Following certification, the system would be sold to operators. This would begin the operational life of the system. Throughout the life of the system, reliability fixes, recertification of components, and maintenance would be required to keep the system operating as intended. At the end of the useful life of the system, a responsible phase-out would be conducted.

Appendix

Full Requirements List

1. The DS delivers packages at a faster speed and cheaper cost than ground shipping.
2. The DS can be loaded and unloaded in a secure yet expedient manner.
3. The DS identifies and chooses landing and takeoff sites so that packages are dropped off and picked up in convenient and safe locations.
4. The DS operates normally after repeated hard landings.
5. The DS can hold and lift multiple medium-sized packages in its cargo hold.
6. The DS insulates its cargo from weather conditions.
7. The DS limits its inertial acceleration as to reduce applied stresses on itself and its cargo.
8. The DS can take off and land vertically, and hover in place.
9. The DS travels without damaging itself, its cargo, nearby people, or nearby property.
10. The DS regularly transmits its position, speed, and heading to air traffic control centers and company network operations centers.
11. The DS can be tracked by consumers and producers of delivered goods via mobile and desktop applications; real-time requests from distributors or customers can reroute, delay, cancel, or expedite the DS.
12. The DS automatically generates a safe and quick route for delivery and autonomously navigates along the route from pick-up to drop-off.
13. The DS navigates efficiently between distribution centers and homes or offices.
14. The DS limits its noise, air, and light pollution during flight.
15. The DS detects and avoids aerial obstructions such as buildings, towers, and cables during terminal phases of flights.
16. The DS cruises above natural and artificial terrain yet avoids restricted airspaces.
17. The DS is able to operate all day with minimal downtime.
18. The DS protects its internal power supply from external damage due to weather or stresses.
19. The DS has the range to bridge the last mile gap between distribution centers and consumer households.
20. The DS differentiates between packages as to pick up and drop off the correct package.
21. The DS protects itself and its cargo from criminal activities, such as hacking, vandalism, or theft.
22. The DS operates normally in mild precipitation and winds; the DS quickly and safely returns to base during severe weather conditions.
23. The DS operates normally overnight and in other reduced visibility environments.
24. The DS avoids harming animals and refrains from crashing after suffering a bird strike.
25. The DS can be interfaced, stopped, and deactivated by police and rescue authorities.
26. The DS retains the option to be piloted by a remote, manual operator.
27. The DS collects, stores, and analyzes telemetry and delivery data; this information can be accessed remotely.

28. The DS is visible during the day and night to individuals on the ground.
29. The DS cargo bay can be accessed by individuals with visual or auditory disabilities.

Link to Full House of Quality

https://purdue0-my.sharepoint.com/:x:/g/personal/tkapoor_purdue_edu/EdB2jvHeLwNFr15WjuCXG34BuuAZol3A9En5qYEOreuTPA?e=LRKJRr

Link to Fault Tree

https://purdue0-my.sharepoint.com/:i:/g/personal/tkapoor_purdue_edu/EZgiQ7ceyBdLvmYIIgiG_GsB2Mz6U8tj44DSpRFUNIBhNg?e=H6R0ho

Full FMECA

ID	Purpose	Failure Modes	Failure Mechanism	Failure Detection	Failure Compensation	Failure Effects	Risk Level (1-Low, 5-High)	Severity	Preventative Measures	Risk Score
Lifting Rotors	Vertical Takeoff/Hover	Broken Blade	Impact, overstress, fatigue	Flight control system	Redundancy, transition to gliding flight	Loss of lift in hover/vertical flight	3	4	Construct of sturdy material, frequent inspection	12
		Motor Failure	Temperature, contamination, over/under-supply of power, moisture, lack of lubrication	Flight control system	Redundancy, transition to gliding flight	Loss of lift in hover/vertical flight	3	4	Construct of sturdy material, frequent inspection	12
Propulsion Rotors	Forward/Reverse Thrust	Broken Blade	Impact, overstress, fatigue	Flight control system	Redundancy, transition to gliding flight	Loss of forward/reverse thrust	3	2	Construct of sturdy material, frequent inspection	6
		Motor Failure	Temperature, contamination, over/under-supply of power, moisture, lack of lubrication	Flight control system	Redundancy, transition to gliding flight	Loss of forward/reverse thrust	3	2	Construct of sturdy material, frequent inspection	6
Wings	Provide lift in forward flight	Structural failure	Impact, overstress, fatigue	Inspection	Transition to vertical flight	Loss of lift in forward flight	2	3		6

ID	Purpose	Failure Modes	Failure Mechanism	Failure Detection	Failure Compensation	Failure Effects	Risk Level (1-Low, 5-High)	Severity	Preventative Measures	Risk Score
Control surfaces	Control drone flight	Structural (control surface) failure	Impact, overstress, fatigue	Inspection	Usage of other control surfaces/lifting motors for flight control	Inability to control aircraft	1	5	Construct of sturdy material, frequent inspection	5
		Failure of control surface actuator	Temperature, contamination, over/under-supply of power, moisture, lack of lubrication	Inspection/Testing	Usage of other control surfaces/lifting motors for flight control	Inability to control aircraft	2	5	Frequent Inspection, Use reliable motors	10
		Control surface binding	Lack of lubrication, warping of components	Inspection/Testing	Usage of other control surfaces/lifting motors for flight control	Inability to control aircraft	2	5	Testing in many conditions	10
Vision System	Detect and identify obstacles, delivery zones, landing zones	Failure to detect	Blocked line of sight, software failure	Inspection/testing	Redundancy	Loss of ability to avoid obstacles, deliver package, take off and land safely	2	4	Redundant systems, frequent inspection	8

ID	Purpose	Failure Modes	Failure Mechanism	Failure Detection	Failure Compensation	Failure Effects	Risk Level (1-Low, 5-High)	Severity	Preventative Measures	Risk Score
Flight Control System	Direction of drone for navigation and safe flight	Navigation Failure	Software	Software testing and validation	Return to base, emergency landing	Loss of ability to find base, drop-off zone, or waypoints	3	3	Extensive testing	9
			Bad input	Input accuracy validation	Return to base, emergency landing	Loss of ability to find base, drop-off zone, or waypoints	2	3	Extensive testing	6
		Control failure	Bad input from air data system	Air data system validation from redundant sensors	Redundancy, emergency landing	Loss of control	3	5	Frequent inspection of air data system	15
			Control software malfunction	Software testing and validation	Emergency landing	Loss of control	3	5	Extensive software validation	15
Power System	Provide power to flight control system and propulsive sources	Battery Failure	Chemical, impact	Voltage Sensor, Inspection	Redundancy	Loss of power in all systems	2	5	Use a reliable battery, swap batteries often	10
		Power Distribution Failure	Wires severed	Voltage Sensors, Inspection	Redundancy	Loss of power in some or all systems	3	4	Frequent Inspection	12

ID	Purpose	Failure Modes	Failure Mechanism	Failure Detection	Failure Compensation	Failure Effects	Risk Level (1-Low, 5-High)	Severity	Preventative Measures	Risk Score
Package Carrying System	Safely retain package, protect package from damage	Retention motor failure	Motor Failure	Inspection	Speed and Altitude Reduction, Emergency landing or return to base, redundancy	Uncomannded Release of Cargo	3	4	Frequent Inspection	12
		Retention latch failure	Impact, overstress, fatigue	Inspection	Speed and Altitude Reduction, Emergency landing or return to base, redundancy	Uncomannded Release of Cargo	2	4	Frequent Inspection	8
		Package container failure	Impact, overstress, fatigue	Inspection	Speed and Altitude Reduction, Emergency landing or return to base	Uncommanded Release of Cargo, Loss of cargo protection	3	3	Frequent inspection and replacement	9

ID	Purpose	Failure Modes	Failure Mechanism	Failure Detection	Failure Compensation	Failure Effects	Risk Level (1-Low, 5-High)	Severity	Preventative Measures	Risk Score
Package Lowering Tether	Lower package to ground at a safe rate	Cable structural failure	Impact, overstress, fatigue	Inspection		Uncommanded release of cargo	2	4	Frequent Inspection	8
		Lowering Motor Failure	Temperature, contamination, over/under-supply of power, moisture, lack of lubrication	Inspection	Use of ratchet mechanism to retain package, emergency landing	Uncommanded release of cargo	3	4	Frequent Inspection, Use reliable motor	12
		Cable Ratchet Failure	Impact, overstress, fatigue	Inspection	Use of motor to secure package	Uncommanded release of cargo	3	4	Frequent Inspection	12
		Hook Failure	Impact, overstress, fatigue	Inspection	Use of retention latches to restrain package, return to base	Uncommanded release of cargo	2	4	Frequent Inspection	8
		Premature Package release	Altimeter failure, structural failure of release mechanism, release motor mechanism failure, software failure	Telemetry	Flight at low altitudes, safe package materials	Uncommanded release of cargo	1	4	Frequent Inspection, Testing of Altimeter and release software	4

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