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An Exploration of Commercial Unmanned Aerial Vehicles (UAVs) Through Life Cycle Assessments

by

Briana Neuberger

A THESIS SUBMITTED TO THE FACULTY OF THE ROCHESTER INSTITUTE OF TECHNOLOGY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN SYSTEMS ENGINEERING

SCHOOL OF INDUSTRIAL & SYSTEMS ENGINEERING
KATE GLEASON COLLEGE OF ENGINEERING

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Abstract

The objective of this study is to analyze the potential for Unmanned Aerial Vehicles (UAVs) to displace current technology and look at how they impact the environment through a delivery transportation model. It is meant to encompass an ecological perspective of producing and using UAVs as well as understand the environmental consequences that accompany it. This paper presents a new way of looking at the uses of UAVs and attempts to apply typical life cycle assessment (LCA) methods to this technology. This research is intended to be used as an initial environmental baseline of drone technology and as a comparative tool for commercial UAV operations in the United States. This study may also provide some insight into government policy rulings and system environmental reporting for this new industry.

Datasets used in this study are available in the ecoinvent library and address small freight lorries compared to simplified UAV technology. Other data sources are used to support model assumptions and fill in information gaps to assure data transparency. This compares energy consumption, material intensity, and emissions generated across three delivery scenarios.

It was found that the energy used to power drones, not the batteries themselves, has the most impact on the environment. Comparatively, trucks have a far reduced impact with the exception of urban land occupation and natural land transformation due to their operation on the road, as opposed to sky. The energy grid mix contributes heavily to what environmental impacts are significant. Depending on the priorities of a company they may consider location as a large factor for drone use and testing.

Although this study is able to complete some knowledge gaps on the life cycle of Unmanned Aerial Vehicles there are points where typical LCA structure is not optimal for this model. The capabilities of a drone are not directly comparable to other technology. This presents challenges when trying to assess the consequences of displacing additional technology.

Keywords

Life cycle assessment, life cycle analysis, unmanned aerial vehicle, drone, lorry freight

Glossary of Acronyms

ALCA	Attributional LCA
CED	Cumulative Energy Demand
CLCA	Consequential LCA
DIY	Do-It-Yourself
EMS	Environmental Management Systems
EO	Electro-Optical
EPA	Environmental Protection Agency
EPP	Expanded Polypropylene
EPS	Expanded Polystyrene
ESC	Electronic Speed Controllers
EVs	Electric Vehicles
FAA	Federal Aviation Administration
FETs	Field Effect Transistors
FMRA	FAA Modernization and Reform Act
GHG	Greenhouse Gases
HS	Hyperspectral
IR	Infrared
ISO	International Organization for Standardization
IT	Information Technology
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LIBs	Lithium-Ion Batteries
LiPo	Lithium-Polymer
MRO	Midwest Reliability Organization
MS	Multispectral
NAS	National Airspace System
NiCad	Nickel Cadmium
NiMH	Nickel-Metal Hybrid
NPCC	Northeast Power Coordinating Council
PC	Polycarbonate
PDB	Power Distribution Board
PS	Polystyrene
RIT	Rochester Institute of Technology
RoW	Rest of World
SMT	Surface Mount Technology
sUAS	small Unmanned Aerial System
TCLP	Toxicity Characteristic Leaching Procedure
THM	Through-Hole Mounting
UAVs	Unmanned Aerial Vehicles
UPS	United Parcel Service
USPS	United States Postal Service
VTOL	Vertical Take-Off and Landing
WECC	Western Electricity Coordinating Council

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1. Introduction

Within the past ten years interest in commercial utilization of Unmanned Aerial Vehicles (UAVs) has skyrocketed [Choi-Fitzpatrick, 2016]. Many large corporations such as Google, Amazon, and Domino's Pizza have taken to the challenge of integrating drones into their businesses. After Jeff Bezos, Amazon CEO, announced the up-and-coming package delivery system marketed as Amazon Prime Air, the perception of drones as "killing machines" has dissipated, being replaced by enthusiasm for this transformative technology to fully emerge in commercial industry [CBS, 2013].

Drones have potential in the private business sector in terms of improving security, reducing business costs, and reducing time-to-market [Bamburry, 2015]. According to information provided by the Federal Aviation Administration (FAA), the use of UAVs is predicted to grow as shown in Figure 1.

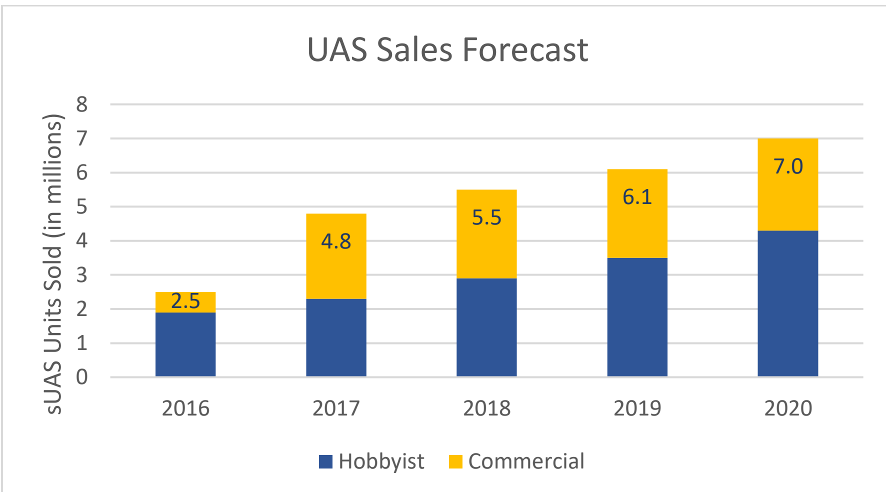

Figure 1 - Prediction of small Unmanned Aerial System (sUAS) units sold per year (in mil) [FAA, Fiscal report, 2016]

Due to this expected growth in the drone industry, it is becoming evident that this technology will be relevant in the near future as businesses realize the value UAVs may add to their mission and revenue. Battery-powered Unmanned Aerial Vehicles may potentially play a key role in surveillance and delivery, to name a couple of applications.

1.1 Regulatory Factors

There are many current regulations in place by the U.S. government which restrict commercial use of drones for business or hobby. There are a few areas of concern regarding this technology which prevent it from fully entering the marketplace, ranging from public privacy and safety to legislative regulations. Not enough is known about the impacts of UAVs to fully assess how they will change society (see Supplementary Material). More information is needed regarding the overall impact of this technology to allow policy makers to pass relevant regulatory decisions.

1.2 Lacking Data

Despite the wide use and benefits of UAVs, there is a severe lack of data regarding the energy and environmental impacts of this technology because it is so new. A great amount of research goes into software and hardware development but there is currently a large knowledge gap on the ecological impact of Unmanned Aerial Vehicles [Stolaroff, 2014].

One valuable question is to determine whether batteries in a UAV produce a significant environmental impact over the lifespan of the drone. If so, do the benefits of drone utilization outweigh the environmental impacts of the multiple batteries they go through in their lifetime [Electronica, 2016]? Such a topic is significant because the improper disposal of lithium-ion batteries for battery-powered electric vehicles (EVs) has been shown to cause human health problems and pollution to the ecosystem [Notter, 2012].

The sensors, or cameras a drone carries, are another high-impact component of the UAVs. Drones carry specialized sensors, electronics, and optical devices which have high cost and maintenance needs. The question surfaces: would there be significant damage to an ecosystem if these sensitive products were not handled or disposed of properly? If a crash occurred, there would be a higher potential for electrical fires and environmental contamination [Klimas, 2015]? Landing failure appears to be a large issue in this adolescent technology, especially due to the lack of landing gear on fixed-wing drones [Hill, 2016].

Products and services that drones displace are not yet well discussed in literature either. The energy consumption and emissions of drones compared to current business methods require further analysis to understand the global impact of UAVs [Stolaroff, 2014]. This study aims to develop a structure for analyzing the ecological perspective of UAV sustainability in the United States. It should be observed that military uses of UAVs will be excluded from analysis in this study.

2. Review of Literature

Although there is little information on the environmental impact of UAVs, there are assessments of comparable technologies. Predictions can be made regarding the impact of drones in commercial applications by pulling from current research on similar electronic products, such as computers, phones, and electric cars, to name a few. To determine what information is known and where the research gaps lie, current literature has been compiled and reviewed. Due to the lack of peer reviewed publications regarding this subject matter, there is a high quantity of internet sources used for this study. Inherently, there are credibility risks when utilizing unvetted online references. As much as possible, consistent and accurate information is used in this study.

2.1 UAV Knowledge Base

2.1.1 UAV Types

There are two basic types of drones currently in use: multirotor and fixed-wing. Multirotor drones have multiple propellers attached to the body of the drone that can perform Vertical Take-Off and Landing (VTOL) as well as hovering maneuvers. The most common of this type is a "Quadcopter," a drone with four propellers [DronesStaff, 2016]. Multirotor drones only cover small areas because their flight time and resistance to elements is very low. These drones typically have a flight time of around 20 minutes, or less, in the air depending on the weight of the payload [Hirvinen, 2010].

Fixed-wing aircrafts typically have a foam shell holding electronics and are hand, or mechanically, launched. They can fly for much longer durations of time and cover larger areas due to their high cruising speeds. Usually these drones are used for mapping large areas or surveying. They can fly for around 45 minutes and are best applied with programmed flights [UAVInsider, 2013]. According to hobbyists and enthusiasts, the life expectancy of both multirotor and fixed-wing UAVs is unknown and varies dramatically based on flight conditions, maintenance, and component fatigue [Dronevibes, 2012].

2.1.2 Applications

Drones have a large variety of applications and fields in which they can be employed.

- Film - these operations include any form of media, arts, or entertainment. Mainly these drones will be used for making movies, filming stunts, or recording televised news. Drone journalism provides low-cost local news coverage and weather assessment without endangering personnel using other transportation. Some current technology and workforce that are displaced by UAVs in this field include helicopters for news coverage, storm chaser personnel, film movement rails or stands, and handheld video cameras.
- Infrastructure monitoring - this category primarily addresses the assessment of structural components such as road integrity [Dobson, 2013], bridge fatigue, powerline condition, mining safety, pipeline corrosion, rooftop inspection, and many more. This takes an at-risk group in the manned workforce and replaces, or supplements, them with machines. Difficult-to-reach areas are also part of this category and include analysis of wind turbine defects, property assessments/tax valuations/appraisals, insurance claims, oil spills, gas leaks, and industry accident notification [Choa, 2015].
- Monitoring/environmental surveillance - this category encompasses wildlife conservation and environmentalism, habitat monitoring, endangered species tracking, and anti-poaching operations. Drones are already being tested to capture heat signatures of black

rhinos and aid in the arrest of illegal poachers [Choi-Fitzpatrick, 2016]. The health of humpback whales is being assessed by drone collection of mucus expelled from their blowholes and later tested [Choi-Fitzpatrick, 2016]. Another application is permafrost analysis in the Arctic to determine climate change [Fraser, 2015]. Drone image collection of specific areas for the purpose of intelligence analysis is another application of UAVs in this field. Examples of this include border patrol, traffic monitoring, collision avoidance in autonomous ships [Johansen, 2016], and bacteria bloom detection in water systems [Ford, 2016]. Companies are exploring the possibilities of replacing helicopters, manned aircraft, and ground vehicles used to observe the environment with UAVs.

- Precision agriculture - this category involves the analysis of crop health or surveying of land specific to agriculture and food products. These operations include monitoring livestock, surveying fields of crops, analyzing irrigation and drainage systems, predicting crop yield, surveying the need for chemical and pesticide application [Bamburry, 2015], and detecting diseases in plants [Zhu, 2009]. Technology that is potentially displaced by implementing drones in this field include tractors, field sprayers, and sprinklers.
- Medical/Emergency - any procedure that requires broad area search or information gathering for health, police, and/or firefighting personnel is placed in this category. Many issues are addressed here, including dispersal of medical supplies and humanitarian aid in natural disasters, hazardous materials and wildfire assessment and mitigation, missing persons response, as well as rally, riot, and protest monitoring. Volcanic ash surveying and eruption damage assessment [McGonigle, 2008], search & rescue [Choi-Fitzpatrick, 2016], and biological sampling or lab specimen transportation [Lippi, 2016] [Amukele, 2015] also fall under this category. Displaced technology includes helicopters, handheld cameras, and satellites.

- Other - all other UAV uses that cannot be classified in the categories above fall under "other." This section includes UAVs for the purpose of education, R&D, real estate, delivery, and more.

2.2 Usefulness of Life Cycle Assessments

Since drone technology is being adopted all over the world and becoming increasingly popular, an environmental perspective would help fill in an important knowledge gap. A Life Cycle Assessment (LCA) is a useful tool for this type of study because it can provide holistic environmental impact analysis, from beginning to end, or partial analysis of one stage of a product. This means that all parts, from raw material extraction to how the drone is used then disposed of, can be analyzed either in part or all together. This could possibly assist policy planners and developers in making more informed decisions on drone technology. LCA is the best method for this study because it looks at the most basic function and components of a device [Venditti, 2012].

An LCA has not been conducted on UAVs but there are partial LCA results on component parts of drones, as well as similar technology and devices.

2.3 Similar Technology LCAs

In looking at alternative, but similar, devices in the electronics field, a few technologies appear comparable to UAVs. Information Technology (IT) devices contribute significantly to the production of greenhouse gases (GHG) due to material extraction and production manufacturing. In general, the larger the mass of a product, the more embodied CO_2 emissions are produced. For example, an Apple iPod has drastically less GHG emissions compared to a Dell laptop. The largest CO_2 emissions among 14 electrical products, according to Paul Teehan's study, are produced in the manufacturing and operation of circuit boards in devices. Assembly, transportation, display, and casing were not as significant factors [Teehan, 2013].

Another electronic component in IT devices is the power supply or, in the case of UAVs, battery type. Studies on lithium-ion batteries (LIBs) in other fields serve as a good model for analysis on drone batteries. LIBs in electronic vehicles suggests that disposal waste can produce hazardous environmental conditions such as water and soil contamination when retired to a landfill. Lithium-ion batteries pass the Toxicity Characteristic Leaching Procedure (TCLP) tests, meeting the standards of the Environmental Protection Agency (EPA) due to the absence of elements such as lead and mercury. However, LIB waste in the state of California is labeled hazardous due to; the presence of cobalt which may pose environmental risks in the future, due to the presence of other heavy metals like copper and nickel; seeping electrolytes; and the potential for landfill fires [Richa, 2016]. As a note, in many cases lithium-ion batteries are not recycled because the process of recovering resources from the battery is more expensive than making new batteries [WMW]. As with any technology, as industry relies more heavily on LIBs, the problems associated with them become more pronounced and impactful.

The waste produced by UAVs is a concern because an overwhelming majority of electronic waste goes into landfills rather than being recycled. Aside from the heavy metals in batteries, there is also the issue of brominated flame retardant coatings that are put on printed circuit boards and the lead used in solder. There is a movement in the United States to encourage the recycling of electronics such as computers that may be applied to drones in the future as well [DeVierno, 2011].

2.4 Current Delivery Processes

The current options for package delivery in the United States are limited, with frontrunners being Amazon, United Parcel Service (UPS), FedEx, United States Postal Service (USPS), and Google Express. These companies apply shipping rates to customer purchases that helps to cover the cost of gas, labor, and packaging materials. A rough estimate of shipping prices and time to delivery was calculated in Figure 2 for each of these companies.

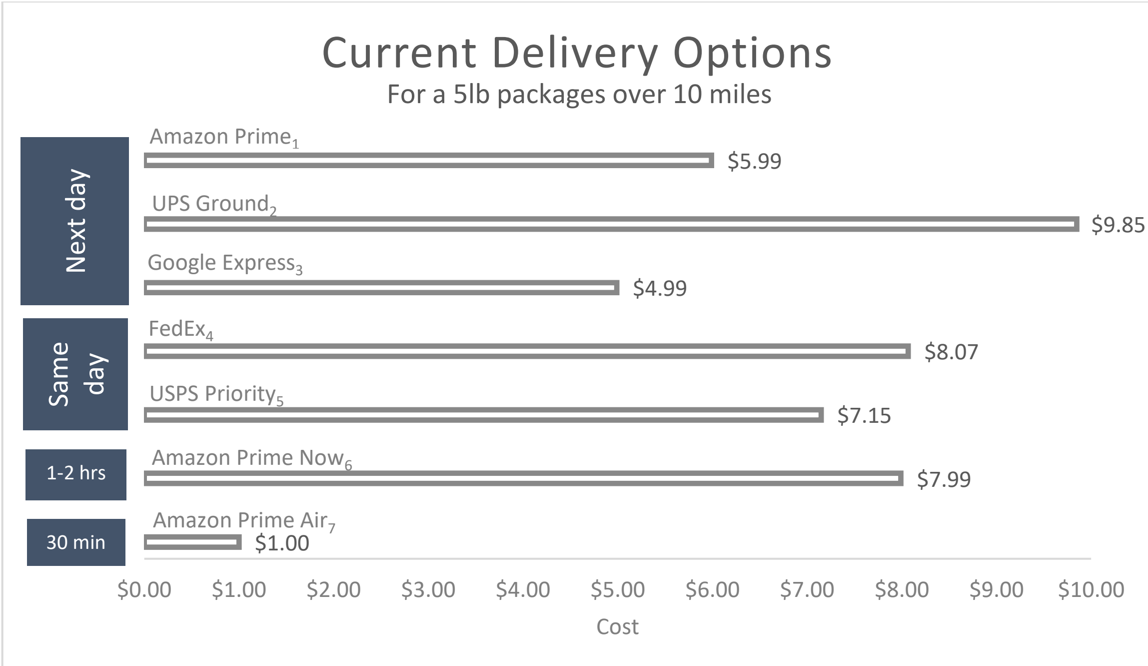

Figure 2 – Amazon Air Prime delivery compared to current options [Keeney, 2015]

The shipment being processed is a 5 lb package sent to a residential area approximately 5 miles away. Figure 2 shows that by using drones in Amazon Prime Air, the cost and time of package delivery can be drastically reduced.

The environmental impact of completing deliveries using drones is yet unknown. Kynan Eng estimates that the energy use of drones in delivery result in 3-5 times the amount of energy used when vans or trucks alone are operated [Eng, 2016].

3. Problem Statement

There is currently no published life cycle assessment for drone technology publicly available. In fact, an ecological perspective on drones in the scientific community has yet to be fully developed. Thus, there is

[1] Amazon Prime shipping cost applies only for orders under $35 [Amazon, 2017]
[2] UPS delivery calculations was a 8x5x1in, 5lbs package shipped from Amazon Headquarters in Seattle, WA to a residential area 10miles away [UPS, 2017]
[3] Google Express costs were $7.99 if item was under $15 total
[4] FedEx delivery cost is a standard rate from 0-150miles [FedEx, 2015]
[5] USPS Priority 1-day shipping for a 85/8" x 5-3/8" x 1-5/8" box
[6] Amazon Prime Now costs $7.99 for 1-hour delivery but is free for 2-hour delivery [Palladino, 2016]
[7] Roughly the cost for service delivery based on how much it would cost Amazon to maintain [Keeney, 2015]

a need for more information regarding environmental impacts of drones and, more specifically, an LCA on the topic [Stolaroff, 2014].

3.1 Problems in Conducting LCA

There are many possible reasons as to why an LCA on UAVs has not been developed yet. Many obstacles prevent direct analysis of this technology.

The technology and manual labor that UAVs are replacing can span many fields of work because they differ so drastically from current processes. For example, in precision agriculture, when a drone takes over crop health analysis and distributing pesticides, it would be replacing a workforce that visually monitors the plants, perhaps monthly aircraft imagery over the field, and tractors used to spray chemicals. In addition, there may be some benefits when employing drones that were not there with previous technology. For instance, property assessments in the retail industry are done manually now and mostly produce images of a house or building from the ground. With drones, aerial views can be captured, the roof can be looked at easily, and areas can be assessed through one image. This adds many factors that were not in this industry before, while also supplementing the manual workforce used to assess the property.

Incorporating UAVs for data collection allows for sampling under weather conditions in which imaging would otherwise be restricted. Such is the case for satellites, which are only useful on clear days when the weather is nice. Since drones are closer to earth they are able to capture imagery even on cloudy days with less restrictions.

A few other issues arise when trying to conduct a life cycle assessment on drones. There are many options for customizability of UAVs for specific applications. Since there is no single design that can be used for every application, the results of an LCA will have limited usefulness. In terms of the sensors that can be attached to these machines, there are many options. Ideally, a representative Universal Payload Interface [Reker, 2015] for sensors would help to provide the most encompassing perspective.

4. Purpose

The goal of this study is to understand the environmental consequences of producing and using Unmanned Aerial Vehicles through the process of a life cycle assessment. To do this, a method of analysis will be proposed for the package delivery application.

5. Methodology

LCAs are based on standards outlined in the International Organization for Standardization (ISO) 14040:2006 "Environmental management – Life cycle assessment – Principles and framework" document. This paper identifies requirements for Environmental Management Systems (EMS) analysis and principles of the scientific approach in an LCA. The stages of this process are outlined in Figure 3.

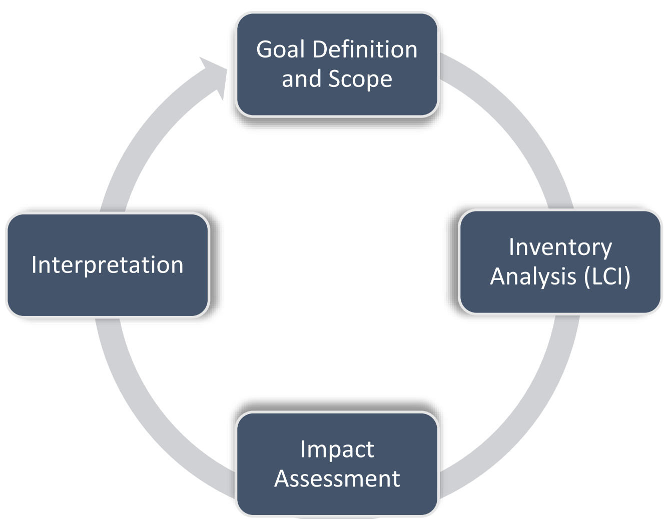

Figure 3 – LCA framework [ISO, 2006]

Following this framework, the environmental aspects of a product can be inspected in a systematic manner. Life cycle assessments are iterative processes, meaning each phase can be re-assessed and revised as many times as needed.

5.1 LCA Framework

5.1.1 Goal Definition

The results of this LCA are intended to be used for commercial UAV product design decisions, government policy rulings, and system environmental reporting. It is meant to support business decisions for non-government UAV applications commercially in the United States as well as influence industry designers to include an environmental focus in development for future UAVs. Policy information can also be supported by identifying environmental improvement potential in material production and use.

The target audience is commercial industry decision makers and global stakeholders in drone production and development, excluding operations in the government sector. It is also geared towards delivery organizations that could benefit from an inexpensive way to transport light packages.

5.1.2 Scope Definition

Unmanned Aerial Vehicles have a large array of functions as previously discussed. They are manual or remote-controlled aircraft which carry payloads for intelligence gathering, transportation of goods, and visual documentation purposes. Due to the various functions that drones can perform more than one method of comparison is needed to assess how UAVs measure up against technology that performs similar tasks. A functional unit in an LCA is a reference to compare and normalize all other data. Figure 4 illustrates how to develop functional units in an LCA.

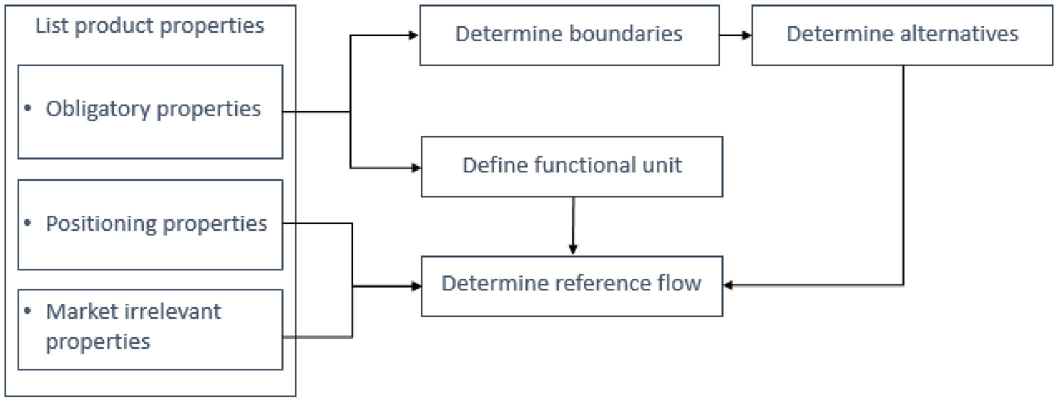

Figure 4 – Functional unit breakdown [LCA, 2015]

The first step in developing a functional unit is to define the product function the product must have to be on the market; properties which are desirable to customers but not needed; and ones that do not play a role in preference. Next, define the market boundaries where the product reaches the customer, geographically and temporally. From the market information, alternative products can be listed. The functional unit is created by using the product functions initially determined, avoiding the use of physical properties. The functional unit size is arbitrary. From there a reference flow can be developed, which is simply some quantity of products needed to fulfill the functional unit. It can typically be compared to a scalable version of product parts. Lastly, a reference flow is developed that compares relatable systems [EPA, 2004].

In this study, the functional properties identified for the Unmanned Aerial Vehicle are: capacity of battery, operating range, flight time, maneuverability, and payload capacity. In this case, it is assumed that price is approximately equal for comparable drone systems thus eliminating cost in the properties.

The drone market is not seasonal nor is it limited to geography. UAVs can traverse a variety of climates and landscapes. Drones that are produced in one part of the world are typically sold to any country. The consumer market for UAVs spans the many applications discussed previously where functionality appears to be the most important positioning property [Droneii, 2016].

Displaced technology is determined based on relevant market segment. For this study, the major technology which is displaced, or supplemented with drones, will be delivery trucks and vans.

A functional unit for this case study can be characterized as the transportation of a 1kg payload within a 5 mile radius delivering 300 packages per day for a time period of two years. Limitations for commercial Unmanned Aerial Vehicles include flying less than 400 ft above ground level, within line of sight, and during the day time. Drones typically last from 50-150 hours before they need to be retired or change parts but there is not enough data currently to get an accurate read on the lifetime of this technology. The average UAV can carry up to 1 kg of payload unless they are specifically designed for heavy lifting.

The reference flow in Figure 5 represents multirotor and fixed-wing drones in a scenario which allows them to deliver 300 packages per day in their lifetime. The third alternative approach shown is a diesel truck comparison.

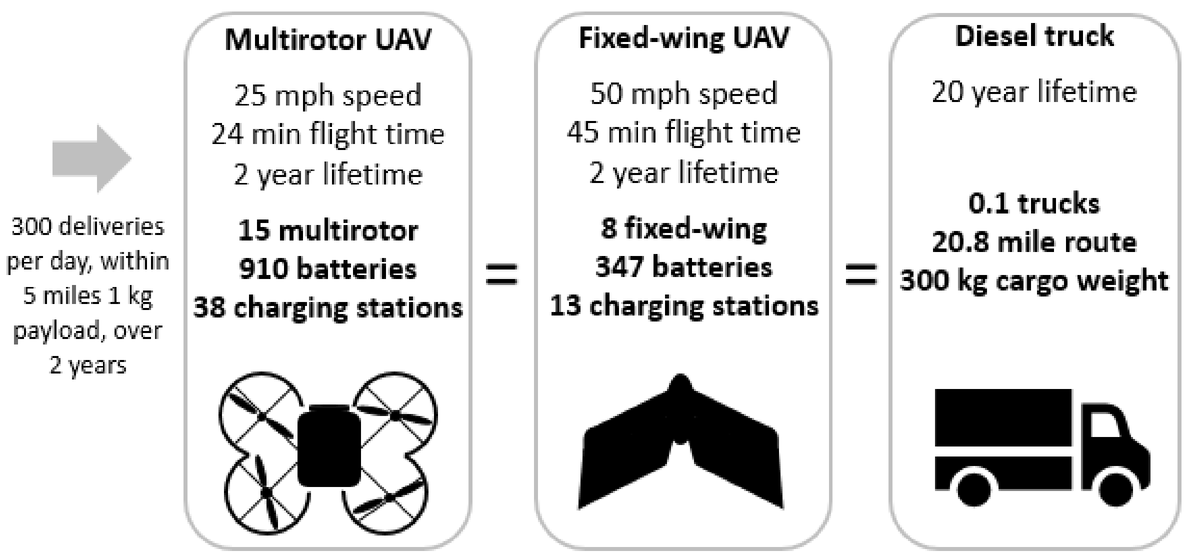

Figure 5 – Reference flow of delivery [Haselbach, 2015]

Assumptions:

1. Drones become obsolete after 2 years of use. This is typically when their warranty expires and companies stop updating firmware on old model [Sudbury, 2015]
2. There are 260 working days in a year
3. Batteries become corrupted or nonfunctional after 120 hrs of use, not including charge time
4. Drones are flown continuously for 8 hrs per day
5. One battery gets between 200-240 min (3.3-4 hrs) of use per day
6. A delivery truck has 1000 lbs cargo capacity
7. Charge rate is 1*Capacity
8. Charging stations match the capacity of the battery
9. Charging stations last up to 10 years and don't need to be retired if batteries are compatible

Figure 5 illustrates the comparative function of two types of drones and a package delivery truck. It shows the speed within range and time it would take a drone to travel 5 miles and deliver one package then return 5 miles back to its starting location. This is based on the speed at which the drones can travel and distance flown in the lifetime of the respective UAV. The possible increased speed without payload on the flight back is ignored in this model. The diesel truck is similar to the P70 package truck used by UPS. Diesel van groups typically run at 10.2 mpg with a 30-gallon fuel tank [Lammert, 2009]. This model takes speed of ascension and landing and calculates them into the average speed of the drone.

The battery must also be considered in the drone lifecycle, as they go through multiple charge cycles over the duration of UAV use. Since the battery is the limiting factor for flight time on each drone, they must be charged after each trip, or 25 minutes of use. Charge time for a single lithium-polymer battery is one hour and the time for charging increases almost linearly with each battery added to a single charging station [Ilyons92, 2016]. As a result, to meet the minimum requirement of drones to deliver 300 packages in an 8 hr workday, each drone would need to have 3 batteries and 3 charging stations, if they did not share. Having multiple drones operating concurrently allows some batteries and charging stations to be shared between drones, in order to optimize flight time.

5.1.3 Life cycle inventory analysis (LCI)

After the goal and scope of the study are properly defined, the next part of an LCA involves data collection as well as quantification of inputs and outputs. The inventory phase of an LCA is where the data collection and process modeling begin. These remain consistent with the goal and scope of the study but also provide cyclical feedback for scope readjustment.

Inputs of energy, raw materials, and associated costs can be tracked through the flowchart in Figure 6. The system can be represented through typical processes such as raw material extraction, processing and preparation, manufacturing and assembly, utilization, and disposal. Each stage outputs emissions to the air, by-products to water and soil, and electricity.

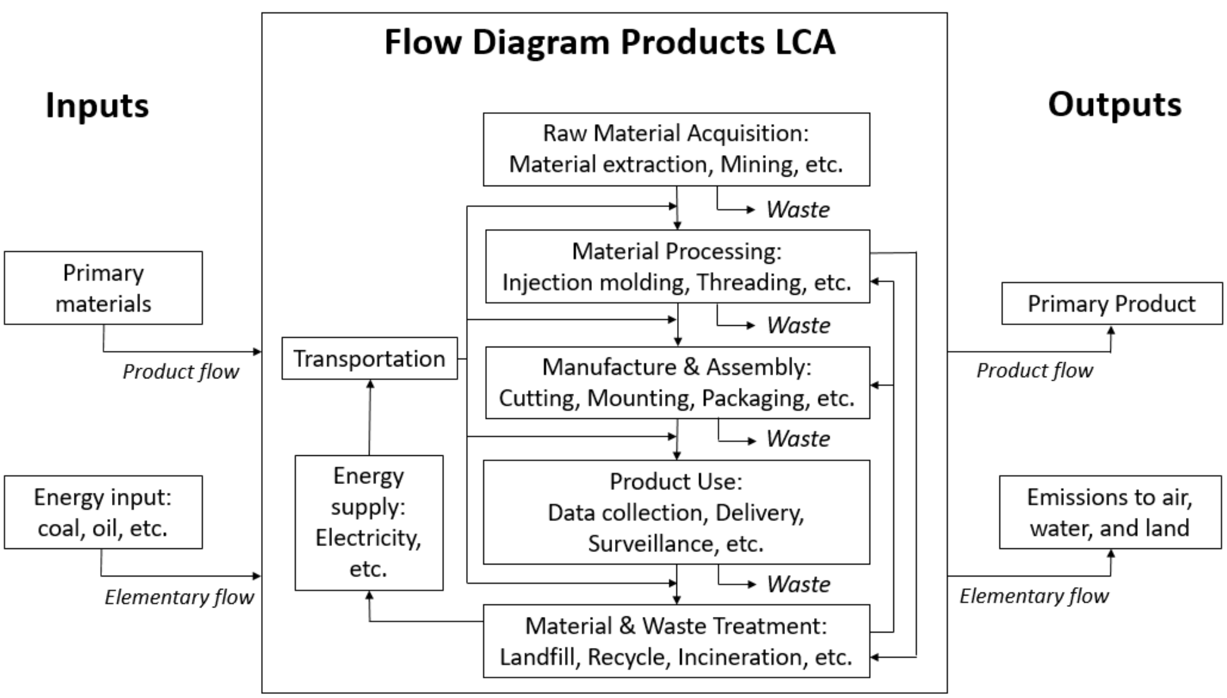

Figure 6 – General model inputs and outputs [ISO, 2006]

The collected data must be validated and related back to the scope of the study. This means translating data into the reference flow using the functional unit.

Figure 7 depicts the generic sub-systems in an Unmanned Aerial Vehicle that will be addressed in this study. The system is powered by a lithium-polymer battery and distributed to the rest of the drone by a Power Distribution Board (PDB). The Electronic Speed Controllers (ESC) connect to the motors and manage the propeller speed. This is controlled by the flight controller which receives directions from the RC transmitter. Components will be discussed later.

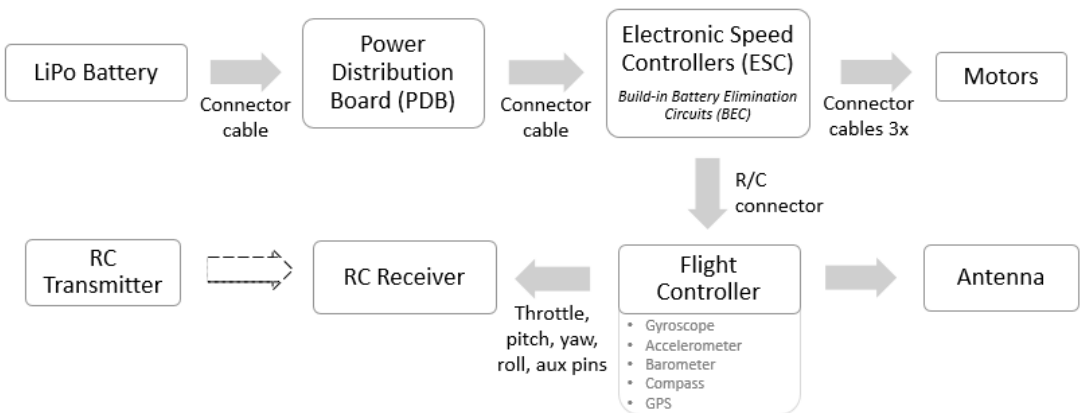

Figure 7 – System components [Benson, 2015]

When determining system boundaries for this study, a few aspects are important to consider:

- As previously mentioned, the entire system, and the interaction between components, for the Unmanned Aerial Vehicle will be analyzed in a delivery-motivated application.
- The study will compare use of UAVs to that of a standard package delivery truck.
- The battery and electrical components are predicted to be the most influential part of the system, due to their short lifespan.

Figure 8, illustrates the system boundaries for this study.

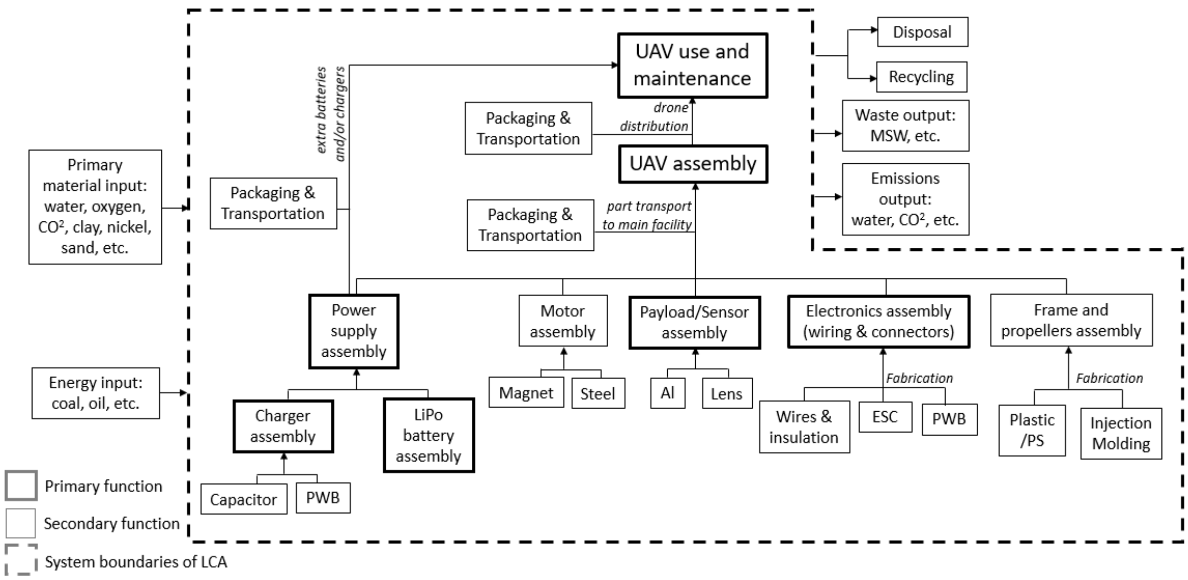

Figure 8 - System boundaries for the LCA of a UAV [Hakimian, 2015]

For simplicity, only the primary and secondary activities within the system flow are shown. Figure 8 does not include the drone's relations with other systems, nor does it consider abnormal operations or accidents in a process or product, such as spills, defects, workplace exposure, etc. The scope of this study does not quantify human health-related issues that emissions may cause but only impacts on the ecosphere. Disposal and waste are not included in the study.

5.1.4 Life cycle impact analysis (LCIA)

The Life Cycle Impact Assessment (LCIA) phase of an LCA is where the input/output inventory data is translated into environmental impact indicators. The LCIA illustrates how results relay from the model to significant impacts on the environment. The elements in an LCIA are determined by the purpose of the study as shown in Figure 9.

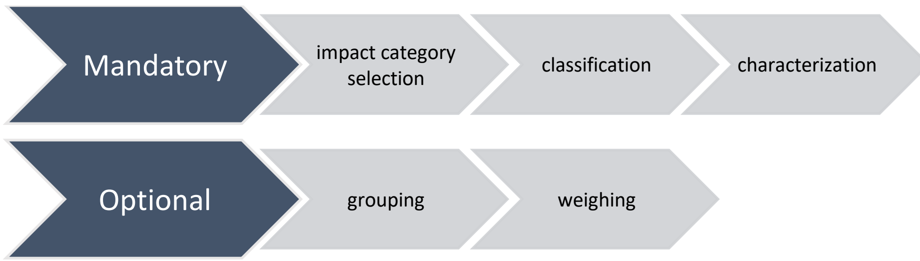

Figure 9 – LCIA elements [ISO, 2006]

The mandatory elements in an LCIA are based on impact category indicators. At the start of an LCIA, an impact category that the study will focus on is selected using LCI results, such as: acidification, climate change, ecotoxicity, resource depletion, etc. This guides the indicators which will be used to quantifiably represent the category. These might include midpoint indicators or endpoint indicators to determine damage to mineral resources or effect on human health [VROM, 2000]. Figure 10 is a nonexclusive list of possible mid and end impact categories.

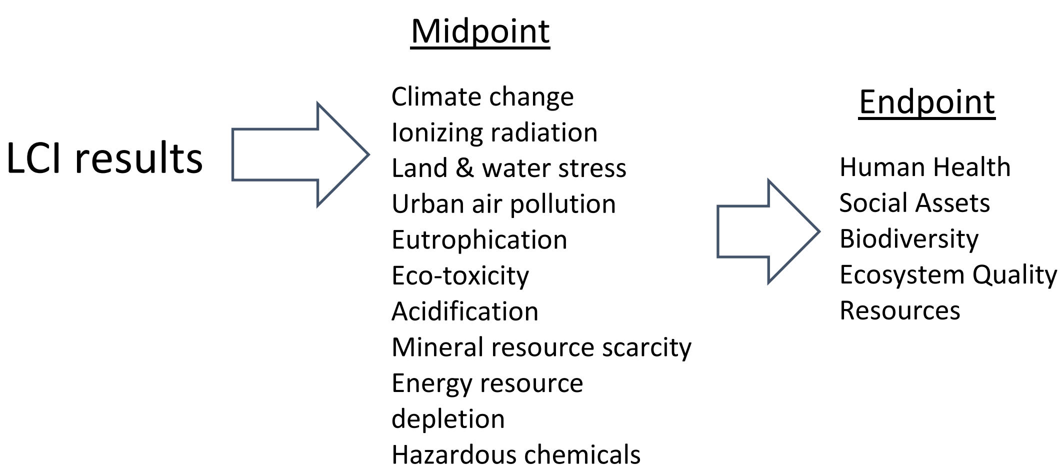

Figure 10 – Mid and end-point impact categories [Huijbregts, 2017]

For example, if fossil fuel use is a significant result from the LCI then there are many impacts that this stressor can have. Categories to focus on for that stressor would most likely include ozone depletion and climate change. The combustion of fossil fuels has been shown to have an impact on greenhouse gas emissions [Bare, 2012].

An LCIA is an incomplete environmental assessment because it only looks at the categories mentioned in the goal and scope of the study. This portion of the LCA is highly reliant on previous information input. Any boundary gaps, data issues, or LCI limitations are transferred into LCIA results.

5.1.5 Interpretation

The interpretation phase of an LCA is where the results of the LCI and LCIA are analyzed together and in relation to the scope of the study. It is in this step that the goal definition is addressed and any lingering questions in the study are answered.

5.2 Reporting Method

The results of this study will be as transparent and objective as possible. This study will produce a "classical" detailed work report in the form of a thesis paper. It will be a condensed, technical overview of the process and resulting recommendations.

6. Data Collection

Data analysis for this study will be based on a package delivery case study in the United States. Primary data will be obtained through hand disassembly of drones. The Agri-footprint library and ecoinvent database will be used in conjunction with the SimaPro LCA software package for product environmental information. Excel spreadsheets will be used as a medium for storing data and visual representation of graphs or charts. It will help organize data as well as graphically display information. The data collected from this study is limited to a set number and type of drones possessed by the Rochester Institute of Technology (RIT) UAV lab in the Carlson building, directed by the Imaging Science department.

In terms of representative data, case studies in any geography can be of use as long as flight conditions are sufficiently described. Since drones are an emerging technology, all data should be within a 20-year timeframe. In this case, the most technologically representative data is superior to time-related or geographical representativeness. This means that, for this study, having accurate information about robust UAVs made by the DJI company in China is preferable to a drone manufactured in the United States that might not be able to carry any extra weight for a payload. Data inventory specifications and applicability of the product are highly important in the environmental impact assessment. An example of data from five drone platforms currently at the RIT UAV lab is shown in Table 1.

Name	Type	Price ($)	Weight (kg)	Body material	Size (mm)	Max Speed (m/s)	Flight time (min)	Payload cap (kg)
DJI Phantom 3 4K	Multirotor	$499	1.28	Plastic	350	16	25	2.00
Precision Hawk 4	Fixed-wing	$18,500	2.40	Plastic	1500	22	40	3.55
DJI s1000	Multirotor	$4550	4.00	Plastic	1045	16	15	7.00
Precision Hawk 5	Fixed-wing	$25,000	2.40	Plastic	1500	22	45	3.55
DJI Matrice 100	Multirotor	$3300	2.35	Plastic	650	22	40	1.00

Table 1 - Current popular UAV platforms

In this LCA study, generic data will be used partially for attributional modeling of a UAV and partially for consequential comparison to displaced technologies. According to SETAC Globe, "attributional LCA (ALCA) aims to describe the environmentally relevant physical flows to and from a life cycle and its subsystems, and consequential LCA (CLCA) aims to describe the environmental consequences of an analyzed decision" [Wolf, 2011].

Data will be collected based on the package delivery use case scenario. A representative drone will be developed based on characteristics required for a multirotor UAV. Data includes distances flown, flight time, battery capacity, depth of discharge, energy spent over distance, rate at which charged, rate of discharge, impact of electricity, and more. Table 2 illustrates rotor drones. DJI is the current leader in the UAV market so the representative model will largely be taken from DJI drones (Source Snow).

Equipment	Qty	Description
Printed Circuit Board	1	Microcontroller containing gyroscope
Electronic Speed Control	4	Controls motors
Frame	1	Outer shell/casing
Motor	4	DC motors for thrust
Propellers	4	8" propellers
Transmitter	1	Communication with ground control
Battery	1	LiPo 3S 2200mAh 20C battery

Table 2 - Multi-rotor model [Shatat, 2014] [Kaputa, 2016]

6.1 Difficulty Obtaining Data

There are a few difficulties in obtaining the data necessary to perform a life cycle assessment with this type of technology. It is relatively new to the commercial market so there is not a lot of information within reach of the public besides what vendors disclose. Many companies consider the material use and amounts proprietary information so it is difficult to get exact data on those. This calls for some assumptions to be made for the assembly process of a drone. Since there are so many UAV models to choose from, data for this study is selected based on availability, representativeness to common UAVs on the market, and ability to carry larger payloads.

7. SimaPro Model

In this study, the drone and truck manufacturing and operations are modeled using ecoinvent unit process market activities. The exact production location and process of drone parts are incomplete and not entirely known, therefore, they are categorized as market activities so SimaPro can take care of any losses in transport that occur [Muller-Beilschmidt, 2012].

7.1 LCI: Electricity, Transport, and Fuel

This section includes life cycle inventory data for electricity, fueling, transportation, and surrounding UAV system.

7.1.1 Electricity

Generally, medium voltage electricity is used in all activities in the use phase. Electricity in production and assembly is built in through pre-constructed processes in the ecoinvent library in SimaPro. Low voltage is used to re-charge the batteries and maintain drones.

Within the market segment, low voltage is described as electricity for household appliances to the service industry range. Medium voltage electricity embodies the production industry. Electricity at high voltage is reserved for energy intensive activities such as coal mining [Schmidt, 2011].

The amount of electricity needed to charge a fully drained LiPo battery is estimated to be 0.66 kWh for one charge per drone for this study. This number is based on testing with a 2000 mAh 6S Multistar LiPo battery measured via the charging station. During this test, the cumulative amount of energy used to charge the battery over one hour is recorded to calculate the energy pull from the electric grid. Due to the inherent inability of this chemical process to be 100% efficient, there will always be more energy used to charge the battery than can be discharged from it. The scalability of this is limited since system energy losses differ depending upon how electricity is transferred after being received from distribution power lines.

Energy used to power the transmitter is also included in the model. Assuming the transmitter is used for 8 hrs per day, a 2 year use is equivalent to 4,160 hrs. The AA batteries hold 40 hrs of charge before needing to be recharged [Liebl, 2013], meaning they need to be recharged 104 times in their lifespans. Energy held in a AA Li-ion battery holds 3.1 Wh.

7.1.2 Power Grid

Energy blocks are created in SimaPro for US electricity using North American Electric Reliability Corporation (NERC) regions shown in Table 3.

Energy Source (%)	ASCC	FRCC	HICC	MRO	NPCC	RFC	SERC	SPP	TRE	WECC
Coal	9.2	21.6	14.8	60.2	3.9	50.3	42.2	53.5	33.4	27.5
Gas	54.4	61.4	-	3.9	41.2	15.7	25.4	26.0	44.9	30.1
Nuclear	-	12.7	-	11.9	32.3	28.6	26.1	3.8	10.7	7.9
Hydro	25.5	0.1	0.9	5.5	13.2	0.7	3.0	1.5	0.1	21.9
Oil	7.4	0.9	67.9	0.3	1.7	0.6	0.5	1.6	0.1	0.1
Wind	2.5	-	5.7	16.3	2.4	2.3	0.4	12.3	9.9	6.4
Biomass	1.0	2.0	3.3	1.7	4.0	1.0	2.0	1.1	0.3	1.5
Solar	-	0.1	0.4	-	0.2	0.1	0.1	-	0.1	2.0
Geothermal	-	-	2.5	-	-	-	-	-	-	2.1

Table 3 – NERC region energy source mix [eGRID, 2014]

**Abbreviations: ASCC (Alaska Systems Coordinating Council), FRCC (Florida Reliability Coordinating Council), HICC (Hawaiian Islands Coordinating Council), MRO (Midwest Reliability Organization), NPCC (Northeast Power Coordinating Council), RFC (Reliability First Corporation), SERC (SERC Reliability Corporation), SPP (Southwest Power Pool), TRE (Texas Regional Entity), WECC (Western Electricity Coordinating Council)*

Since the location for the study was spread across the US, an average was taken to represent an energy mix as shown in Table 3. This energy mix could be altered to represent a single region based on drone manufacturing and use. The cumulative energy mix is modeled for the US based on region as shown in Figure 11 and based on fuel source as shown in Figure 12.

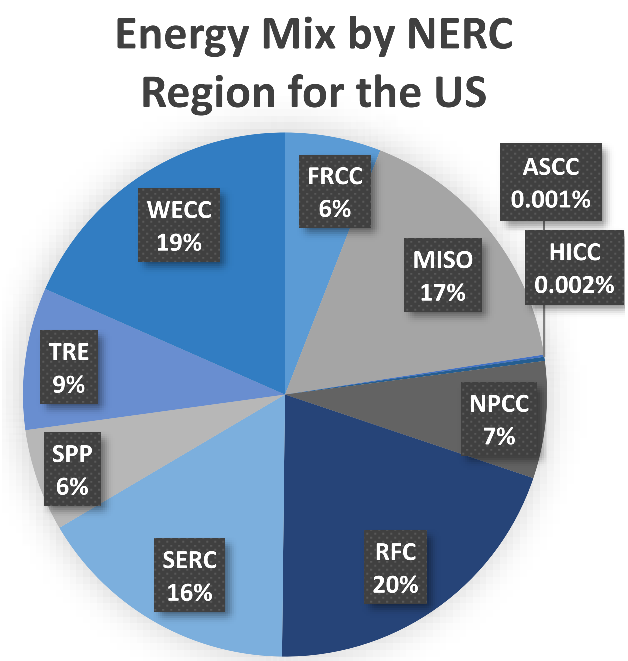

Figure 11 – Breakdown of energy mix by region [NERC, 2016]

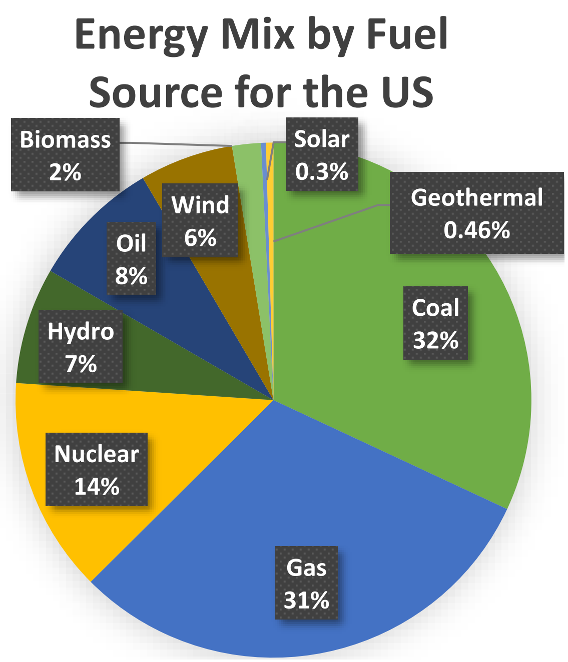

Figure 12 – Breakdown of energy mix by fuel [NERC, 2016]

This energy mix is used for powering drone use and recharging the batteries. It is not representative of material acquisition or drone manufacturing.

7.1.3 Energy Losses

Figure 13 shows the total energy losses throughout the system, from power plant to drone battery. The libraries in SimaPro adjust for energy loss from the power plant up through distribution power lines.

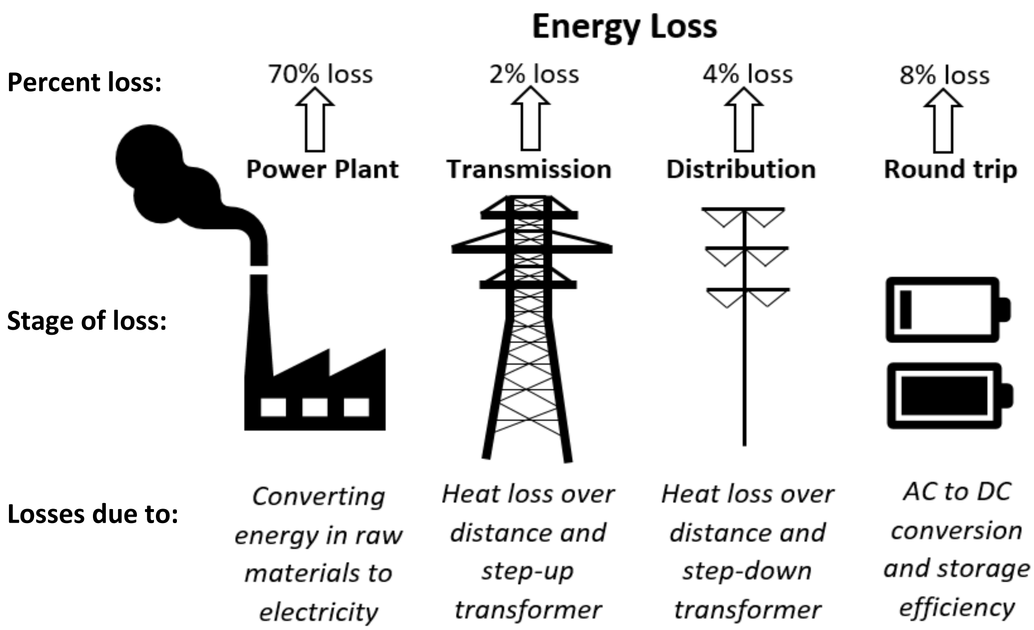

Figure 13 – Energy loss [Wirfs-Brock, 2015]

Only one-third of a power plant's energy makes it onto the grid as electricity. After that, it is transmitted over high-voltage power lines across the country, where there is a 2% energy loss through heat. From the high-voltage power lines, energy is distributed to residential areas through low-voltage power lines. Transformers step down the electricity so it is safe for use, where 4% energy loss occurs. There is approximately an 8% roundtrip loss in the batteries.

7.2 LCI: Material Assembly

The major components that are applicable to all drones must be represented in the SimaPro model. Those include the frame, propellers, optical sensor, electronic speed controllers (ESC), motors, power distribution board (PDB), and transmitter. Figure 14 illustrates these components and where they are placed in the drone assembly.

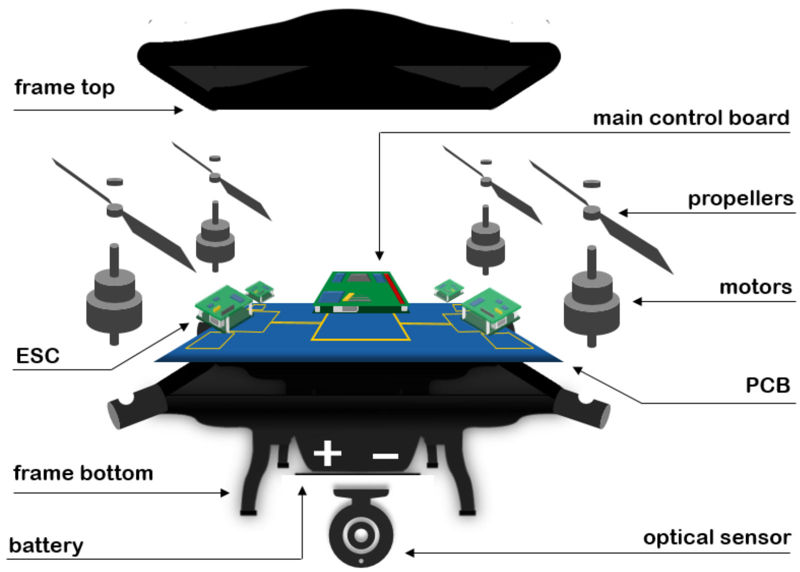

Figure 14 – Simplified multirotor exploded assembly diagram [Greco, 2016]

Figure 14 illustrates the major components found in a multirotor UAV system. Between the top and bottom parts of the frame, there are several electrical components, including Electronic Speed Controllers (ESC), a main control board, and the Printed Circuit Board (PCB). On the perimeter, there are between 4 and 8 motors and propellers. Underneath, the lithium-ion battery is encased and the optical sensor is attached. The fixed-wing UAV system varies in only a few aspects. The body is made of a different material and there are fewer electrical components and motors. Figure 15 illustrates the design for a fixed-wing UAV model. The only differences here are the frame material and battery size which will be discussed later.

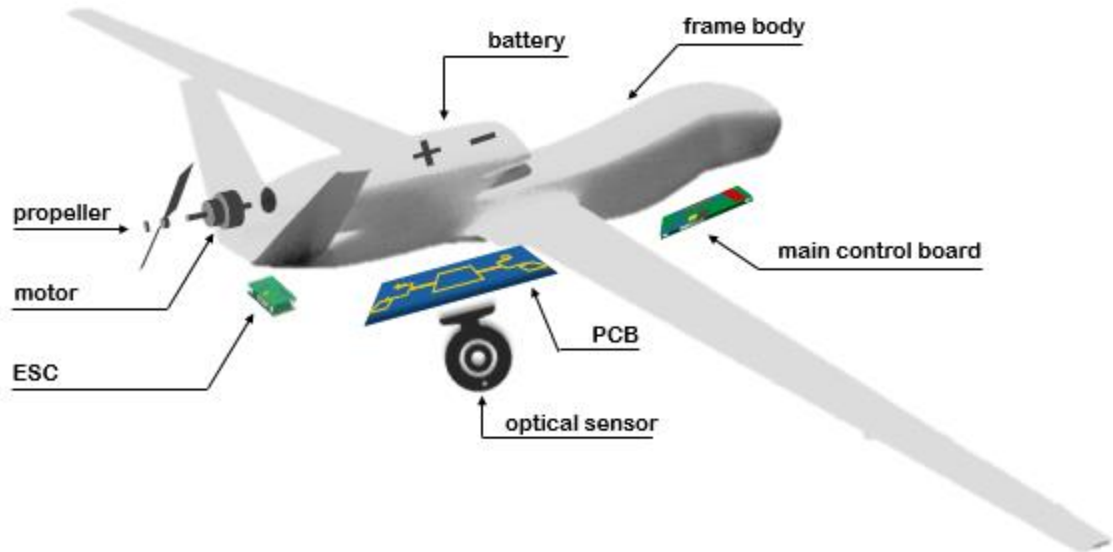

Figure 15 – Simplified fixed-wing exploded assembly diagram [Ellerbroek, 2014]

The placement of these parts may vary by drone manufacturer but they will more-or-less remain similar.

7.2.1 Frame & propellers

There are many different materials from which UAV frames are made. Some of the most common are carbon fiber, glass fiber, and aluminum [Korey, 2014]. The fixed-wing aircraft is made of low density foam, typically Expanded Polypropylene (EPP) or Expanded Polystyrene (EPS), and are much larger in size [Ellerbroek, 2014]. Table 4 and 5 illustrate the properties of drone body materials input into SimaPro using the ecoinvent database. The multirotor is modeled with polycarbonate (PC) and the fixed-wing is modeled with polystyrene (PS).

242g Multirotor frame assembly	**Input/Output**	**Input in SimaPro**
Materials/fuels	175g PC body shell	Polycarbonate {GLO}|market for | Alloc Def, U
	42g PC legs	Polycarbonate {GLO}|market for | Alloc Def, U
	35g PC propellers	Polycarbonate {GLO}|market for | Alloc Def, U
Processes	242g PC Injection molding	Injection moulding {GLO}|market for | Alloc Def, U

Table 4 – Multirotor frame assembly in SimaPro

1,050g Fixed-wing frame assembly	Input/Output	Input in SimaPro
Materials/fuels	1,050g PS body shell & wings	Polystyrene, expandable {GLO}| market for | Alloc Def, U
Processes	1,050g PSC Injection molding	Injection moulding {GLO}|market for | Alloc Def, U

Table 5 – Fixed-wing frame assembly in SimaPro

The weight of the frames is interpreted from drone dimensions and density of the material they are made from. The fixed-wing drone is representative of a large 4.5 kg drone with a 2200 mm wingspan [Cheng, 2017]. Propellers are typically made from the same materials as the multirotor frames so are included in the frame process.

7.2.2 Battery

UAVs use lithium-ion batteries (LIBs), although nickel cadmium (NiCad) and nickel-metal hybrid (NiMH) were used in older model drones. Lithium-polymer (LiPo) batteries are the most common due to their high energy-density, light weight, and small self-discharge rate [Notter, 2012].

When deciding which battery to use to power a UAV, a few factors are important: voltage, capacity, and discharge rate. LiPo batteries have a nominal voltage, which is the resting voltage of the pack and approximated to be 3.7V. If there are two LiPo battery cells in a pack, typically referred to as 2S, or 2 cells connected in series, then voltage is 7.4V. Three cells connected in series (3S) is 11.1V, and so forth. When fully charged, LiPo batteries can reach up to 4.2V per cell and discharge safely to 3.0V per cell [Schneider, 2017].

Capacity is how much charge the battery can hold before needing to be recharged. It is defined as drain on battery to discharge in one hour. However, the capacity is directly related to the size and weight of the battery. Along with the capacity, the discharge rate, or C-rating, determines how fast the battery can be safely discharged.

$$max\ continuous\ amp\ draw = Cap\ (amps) * "C"\ Rating$$

Exceeding this discharge rating would result in the battery degrading faster than normal or an unsafe failure. Using batteries of higher capacity allows for the UAV to be heavier and carry a larger payload while still having the same battery life, or flight time, as a battery with lower capacity. The tradeoff, however, is that the more power the battery can hold, the larger and heavier it becomes.

Assuming a LiPo battery of 4500 mAh capacity, 6S 22.2V with 30C (discharge rate) weighing around 350g, Table 6 shows the SimaPro input specifications.

350g of LiPo battery	**Input/Output**	**Input in SimaPro**
Materials/fuels	350g LiPo battery	Battery, Li-ion, rechargeable, prismatic {GLO}| market for | Alloc Def, U

Table 6 – Battery assembly for large LiPo

The LiPo batteries have a lifespan of around 300-400 cycles, with a cycle being one trip out and back for the drone [Schneider, 2017]. After each cycle, they need to be charged. The battery charger for drones is similar to that of a laptop battery charger [Wells, 2015] except a bit denser and are sometimes built to handle more than one battery. Table 7 represents the SimaPro model of a drone charger. Typically, batteries take approximately one hour to charge fully with a recommended charge rate of 1C, or 1 times the capacity [Mikowski, 2015]. It should be noted this study uses series charging and not parallel because batteries would not often be charged concurrently and is dangerous to put batteries with a voltage difference over 0.1V in parallel [Mikowski, 2015].

1p of Charger	**Input/Output**	**Input in SimaPro**
Materials/fuels	1p Charger (battery)	Power adapter, for laptop {GLO}| market for | Alloc Def, U

Table 7 – Battery charger assembly

As long as there are no specialty connections for the battery, and the charger is able to handle the battery voltage, there is no reason to retire a charger if switching to a new drone. For this study, the lifetime of a drone charger was approximated to be 10 years.

7.2.3 Motors

The voltage of the battery used will determine how fast the drone goes. Voltage is directly related to the speed of the electric motor, so if there is a brushless motor with a Kv constant of 3,500 then it spins at roughly 3,500 RPM per Volt with no load applied [Schneider, 2017].

Motors used in UAVs are similar to those used in electric scooters in regard to size, power, and model. The ecoinvent database has a pre-build scooter motor as shown in Table 8.

26.5g of 1 Motor	Input/Output	Input in SimaPro
Materials/fuels	26.5g Motor (single motor)	Electric motor, for electric scooter {GLO}| market for | Alloc Def, U

Table 8 – Motor assembly

7.2.4 Electronic Speed Controller

An ESC is used to power electric brushless motors on the drone. They take DC voltage from the battery and turn it into multiphase AC voltage that goes out towards the motor and receiver to give control over the craft speed. Within each ESC there is a microcontroller which redirects power out of each wire from the battery and determines when Field Effect Transistors (FETs) turn on. FETs are on the back of the ESC and weigh around 1 g each [RCModelReviews, 2012]. These small panels switch the voltage between them to create AC that signals the motor to turn. Most often, ESCs fail when the FETs overheat. A thermoplastic heat shrink is used around the ESC to hold wiring in place and act as an insulator. The heat shrink tubing shrinks by 40-50% of its original size. [MyRCMart, 2015]. A heat sink, which is a device to absorb unwanted heat, keeps the FETs from overheating [CableOrganizer, 2017]. Finally, aluminum electrolytic capacitors complete the ESC by managing the pulses created when the DC switches to AC and reduces noise. The ESC is included in the Printed Circuit Board (PCB) for the SimaPro model because the two components are made from the same materials and much of the time the ESC are directly attached to the PCB.

7.2.5 Printed Circuit Board

The Printed Circuit Board (PCB) is used to manage signal connections and hold microchips in place. In this model, the PCB is surface mounted and lead-free. Although Through-Hole Mounting (THM) was very popular before the 1980s, Surface Mount Technology (SMT) has mostly phased it out. SMT is sufficient for drone technology, although THM would prove more consistent for tougher flights [Optimum, 2017]. Again, the PCB is combined with the ESC in Table 9 because they can be modeled on one board.

58.15g of PCB	**Input/Output**	**Input in SimaPro**
Materials/fuels	6.67g Heat shrink	Polyvinylchloride, bulk polymerised {GLO}| market for | Alloc Def, U
	11.5g PCB	Printed wiring board, surface mounted, unspecified, Pb free {GLO}| market for | Alloc Def, U
	1.8g Capacitors	Capacitor, electrolyte type, < 2cm height {GLO}| market for | Alloc Def, U
	8.6g Padding	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Def, U
	5g Plastic casing	Polycarbonate {GLO}| market for | Alloc Def, U
	5g Aluminum	Aluminum, cast alloy {GLO}| market for | Alloc Def, U
	18g FETs	Transistor, surface-mounted {GLO}| market for | Alloc Def, U
	1.58g Wiring	Cable, unspecified {GLO}| market for | Alloc Def, U
Processes	8.6g Foaming	Polymer foaming {GLO}| market for | Alloc Def, U
	5g Casing	Injection moulding {GLO}| market for | Alloc Def, U

Table 9 – Printed Circuit Board assembly [Greco, 2016]

Assume manual labor is used to put together the PCB. The Phantom 3 circuit board alone weights about 59 g [Benchmark, 2017] so we assume this weight.

The amount of wire used to connect the PCB to the motors is estimated to be around 8.5 in for all four ESCs. This may vary depending upon the number of propellers on a multirotor drone and size of the PCB. Wire gauge is assumed to be 18AWG which weights approximately 4.92lbs per 1000ft [ColonialWire, 2013]. Capacitors are about 5g each [Greco, 2016]. Depending on the ESC attachment, there can be many small capacitors or a few larger ones on the drone. The DJI Phantom 3 has an integrated ESC circuit board with only 2x 220 uF 25V capacitors [PartsExpress, 2016], which weigh about 0.6 g each. The original Phantom drone has four separate ESCs connected with wires to a main PCB where the flight controller is located [Phan, 2013]. The flight controller is another PCB that contains the gyroscope made out of a small amount of aluminum alloy [Konze, 2013].

7.2.6 Transmitter

The transmitter is the main control system that allows a user to manipulate the drone's path, basically a remote controller. Within a transmitter is another PCB with a few wiring components, small battery, and a joy sticks that help direct the flight path. Table 10 illustrates a simple transmitter makeup.

305.5g of RC Transmitter	**Input/Output**	**Input in SimaPro**
Materials/fuels	11.5g Wiring	Cable, unspecified {GLO}| market for | Alloc Def, U
	189g Casing	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Def, U
	90g Battery	Battery, Li-ion, rechargeable, prismatic {GLO}| market for | Alloc Def, U
	15g Electronics	Printed wiring board, surface mounted, unspecified, Pb free {GLO}| market for | Alloc Def, U

Table 10 – Transmitter assembly [Dunnill, 2015]

There are multiple reasons why drones would not require handheld transmitters, one of which is that many UAV systems are preprogrammed to fly a certain route. For this study, a transmitter was included since they are sold with nearly all drones and can be used even during a preprogrammed flight.

7.2.7 Sensor

To focus on the drone configuration itself, the sensor modeled in this study is overly simplified to illustrate a rudimentary imaging system. The body of a sensor is a polycarbonate compound with 10-20% glass fiber [MadeHow, 2010], an array of silicon, and glass lens, illustrated in Table 11.

335g of optical sensor	**Input/Output**	**Input in SimaPro**
Materials/fuels	121g Lens	Flat glass, coated {GLO}| market for | Alloc Def, U
	372.88 mm^2 Pixel array	Single-Si wafer, for electronics {GLO}| market for | Alloc Def, U
	8.144g Casing	Polycarbonate {GLO}| market for | Alloc Def, U
	3g Wiring	Cable, unspecified {GLO}| market for | Alloc Def, U
Process	121g Lens cutting	Metal working machine, unspecified {RoW}| production | Alloc Def, U

Table 11 – Sensor assembly

Since there is a great deal variability that goes into the development of a specific sensor, it is not modeled fully in this study. There are many optical sensors that can be adapted to fit on a UAV, including, but not limited to, Infrared (IR), Multispectral (MS), Hyperspectral (HS), Thermal, Visible, and LiDAR. For the purposes of package delivery, a simple electro-optical (EO) sensor is sufficient.

Also, the type and size of sensor used impacts the amount of electricity being drawn from the system to operate this equipment. In effect, the flight time of a drone may change.

7.2.8 Other

Many other small parts of the drone can be disregarded as they are not significant factors in the weight of the system. This includes, for example, all nuts and bolts, hex spacers, vibration damping, motor mounts, zip ties, screws, etc. The mass of the materials used for these parts is small enough such that they don't contribute to the drone's environmental impact as a whole in a significant manner.

7.3 LCI: Operations

7.3.1 UAV Operations

For this study the materials from SimaPro to represent the system include a drone without a battery, a battery, a charger, and energy.

The flight time depends on the size of the battery and energy draws from the electronics as mentioned previously. Depending on the battery capacity, the charge energy pull differs. Batteries with greater capacity require more energy to fully charge compared to batteries with lower capacities. Additionally, due to the inefficiencies in the charging process, more energy needs to be taken from the electricity grid than is used in the battery. This means that batteries' rated capacities do not accurately represent the energy needed from the grid to fully charge them.

7.3.2 Truck Operations

Based on the freightliner Ford 700 stepvan [Bush, 2017], the delivery truck is modeled similar to a FedEx or USPS truck. This is in a class 2 vehicle category being between 6,001 to 10,000lbs [Collins, 2014]. The ecoinvent library already has a network of transportation vehicles modeled. The stepvan that most people are familiar with when thinking of truck package delivery is closely related to the ecoinvent process for a small lorry freight that has a size of 3.5-7.5 tons and average load factor of 0.98-4.98 tons, as shown in Table 12. A Load factor is defined as the ratio of average load to total vehicle freight capacity [EEA, 2001]. This model considers vehicle manufacturing, operation, fuel consumption, maintenance, road construction traffic.

1p stepvan	Input/Output	Input in SimaPro
Materials/fuels	3,245tmi stepvan	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {GLO}| market for | Alloc Def, U

Table 12 – Stepvan assembly

The Euro 3 emission class was selected because many of the current delivery trucks are 10-20 years old and have not been retired, making the 2000-2004 manufacturing year very relevant [Simons, 2013].

The truck reference unit is ton miles. To determine the material use, the distance traveled and cargo payload is needed. The maximum weight that one of these stepvans can carry, according to USPS, is around 1000 lb in cargo [GreatBusinessSchools, 2017]. The percent cargo can be changed according to what is being transported, but for this study it is assumed to be 2/3 full or 0.3 metric tons. The average route is 20.8 miles in a day, roundtrip. In fact, 53% of USPS delivery drivers only go 10-19 miles per day [GreatBusinessSchools, 2017]. Therefore, for 2 years, assuming 260 working days per year, the total mileage calculates 3,245 ton-miles.

7.4 LCI: Disposal, Recycling

Waste scenarios are omitted from this study. Most materials would go to landfill or be recycled but there is currently no real disposal program for drones. The majority of these systems are either stored or donated to UAV enthusiasts.

8. Results

8.1 Process contributions

The results from SimaPro show that the most significant materials in the multirotor drone system are the electronics. The fixed-wing drone produced similar results. Figure 16 illustrates midpoint ecological indicators from the ReCiPe method using hierarchist (H) perspective. The ReCiPe European method is used for analysis with the hierarchist perspective as the default because it is between long- and short-term based models and incorporates both optimistic and precautionary thinking [PRe, 2017].

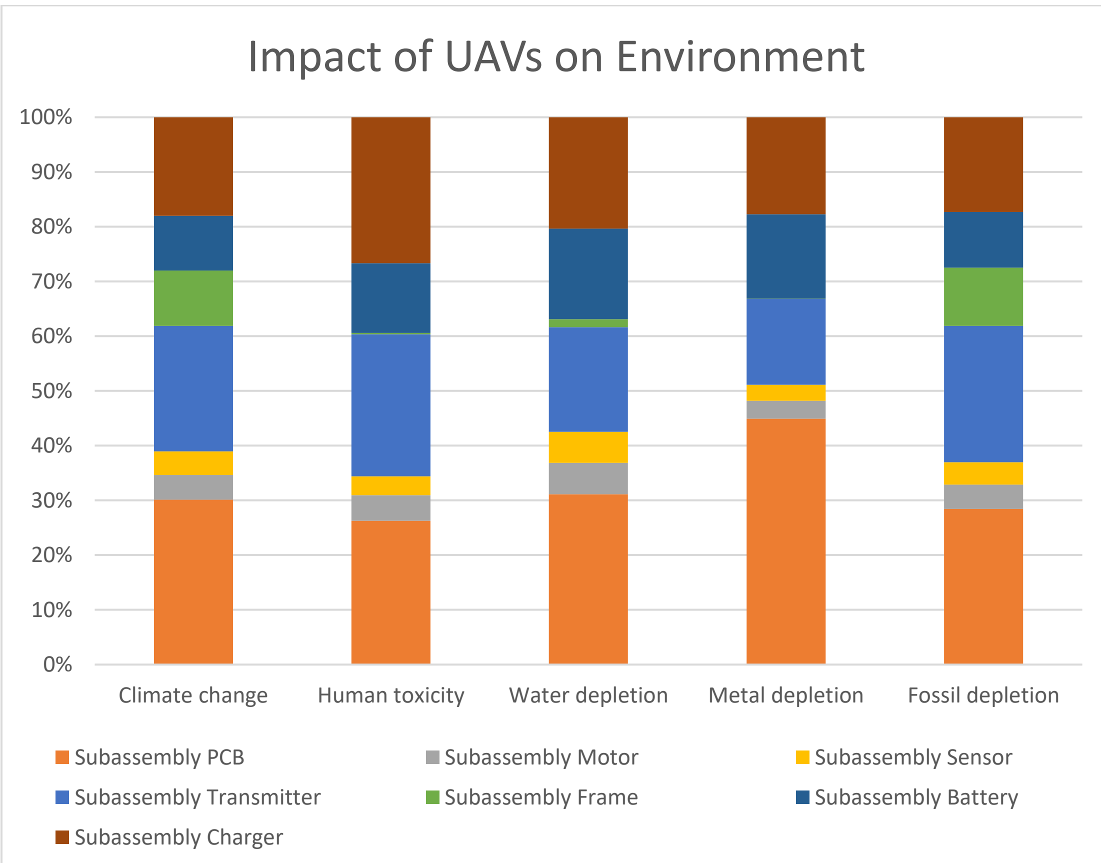

Figure 16 – Multirotor midpoint impact analysis
**Note that this is a model of only part materials and assembly. It does not include the energy used to fly the drone.*

Figure 16 shows the overall breakdown on assembly parts on the environment, excluding the use phase. Fossil depletion refers to fossil fuel use and extraction. Metal depletion is associated with the decreased grade of minerals from Iron (Fe) equivalents. Water depletion is higher here for the electronic parts and is the amount of fresh water consumption. The human toxicity category references the change in toxicity of a chemical based on environmental accumulation. Finally, the climate change category is global warming potential per the emission of greenhouse gases [SimaProDataManual, 2017].

Figure 17 illustrates an energy consumption graph that reflects the assembly and use phases separately in this study.

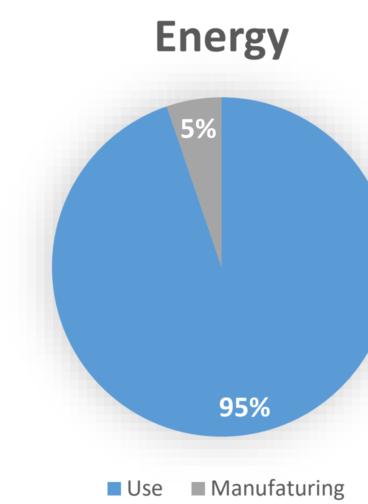

Figure 17 – Multirotor energy analysis

It is clear to see that the use phase dominates the drone life cycle from Figure 17. This is due to the fact that the batteries take so much energy to charge and fly the drone that they are the main source of energy pull from the grid in this system. The energy used to manufacture a drone either man-made or in assembly line is negligible.

8.2 Overall results of alternatives

To examine how drones relate to a delivery vehicle, the multirotor and truck transportation systems are modeled and compared using the ReCiPe midpoint method, again from the hierarchical perspective. Figure 18 shows a few impact categories of these processes when comparing 15 multirotor drones with 910 batteries and 38 charging stations to 1 light-weight stepvan on a 20.8 mile route 2/3 full. For this comparison, the energy pull for the multirotor drone is being modeled with a 15.2V, 4.8 Ah battery with 0.1 kWh per charge energy pull.

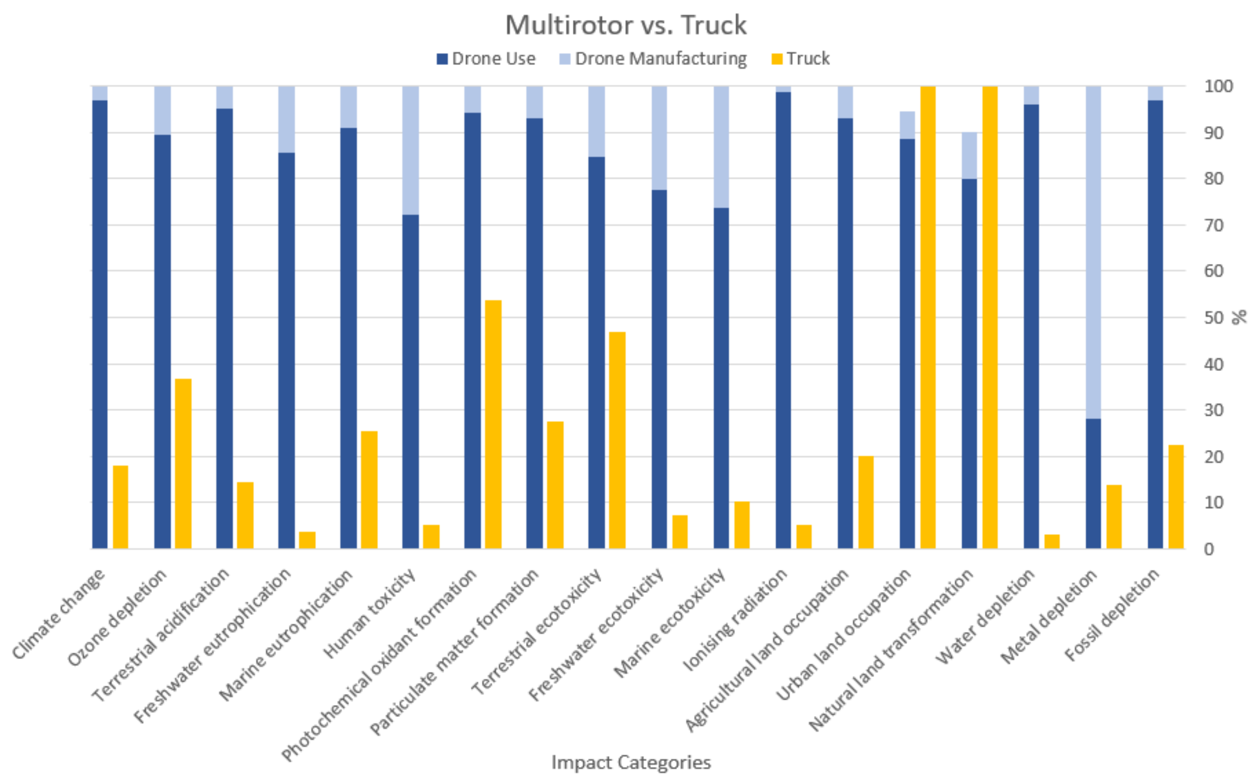

Figure 18 – Drone and truck midpoint impact comparison

Figure 18 shows the use and manufacturing phases of the multirotor drone compared to the truck. The majority of the results from the multirotor are caused by the large energy pull required to operate these machines for 2 years.

The fixed-wing drone was left out of this part of the study since it was not an accurate representation of a technology that could be employed to deliver packages. Due to its design, the fixed-wing drone would need a landing strip to stop at a customer's house a device to relaunch it into the air. The fixed-wing drone is shown in the sensitivity analysis section as an abstract comparison.

Figure 19 illustrates the energy distribution for a single multirotor drone used to delivery 300 packages per day annually using the Cumulative Energy Demand (CED) method in SimaPro.

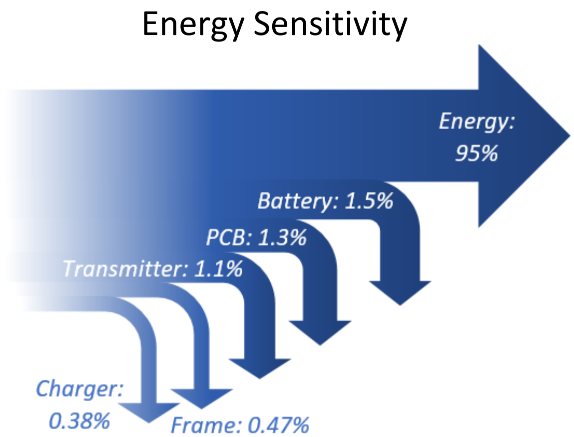

Figure 19 – Sankey diagram

9. Sensitivity Analysis

From the previous section, it is clear to see that the largest environmental impacts from the drone arise in the use phase. Since the manufacturing phase was not as significant, the only area of interest that was explored is frame material. The type of material used to manufacture the UAV frames had a small impact on the environmental indicators though. To further explore a few areas of this study, a sensitivity analysis is done. Here, a few variables are manipulated to understand their impact on the model provided a few assumptions.

9.1 Number of deliveries

A truck can have a larger capacity than 300 1 kg packages, and the number of deliveries depends largely on the area. Rural locations make up only 17% of a USPS fleets' route [GreatBusinessSchools, 2017]. That means 83% of driving is in the city driving so there is more potential for a higher number of deliveries in a day. Doubling the number of deliveries that a truck can make in a day, doubles the number of drones needed: instead of 15 multirotor drones, 30 are used. This doubles the impact because in total there is twice as much energy being used.

9.2 Payload

Changing the cargo weight on the stepvan can reflect the types of packages being delivered. Smaller, lighter shipments will take up less room on the truck and have a smaller impact on total cargo weight. After analyzing the results of a stepvan at 100% capacity, 80% capacity, and 60% capacity, it was clear that the ecological impact scaled with cargo load.

9.3 Life time of UAVs and Batteries

Changing the useful lifetime of the drones themselves did not have a large impact on the environmental categories unless the timespan was altered drastically. To determine if there is ever a scenario where the drone manufacturing phase outweighs the use phase, the energy mix for 5, 10, and 15 days were analyzed rather than the 2 year life for the original study.

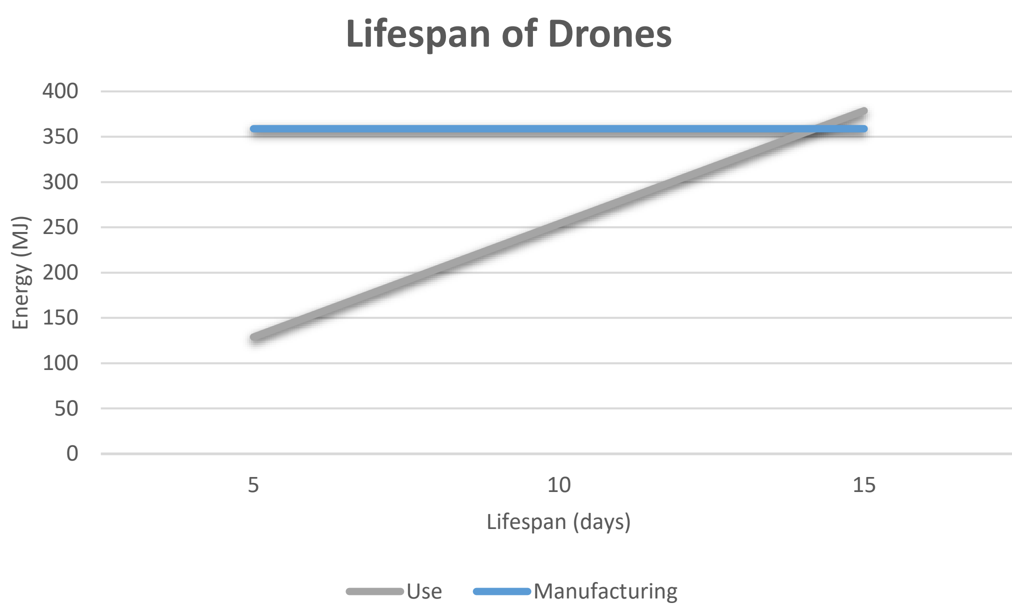

Figure 20 – Decreased lifespan

The results in Figure 20 show that the drone would need to last less than two weeks for the manufacturing phase to overcome the energy used in the use phase.

Also, if a multirotor drone was able to make more deliveries in a single charge, then the results of energy use decreases drastically. Figure 21 illustrates scenarios where drone batteries are more efficient and require less charges to do the same 300 deliveries in a day.

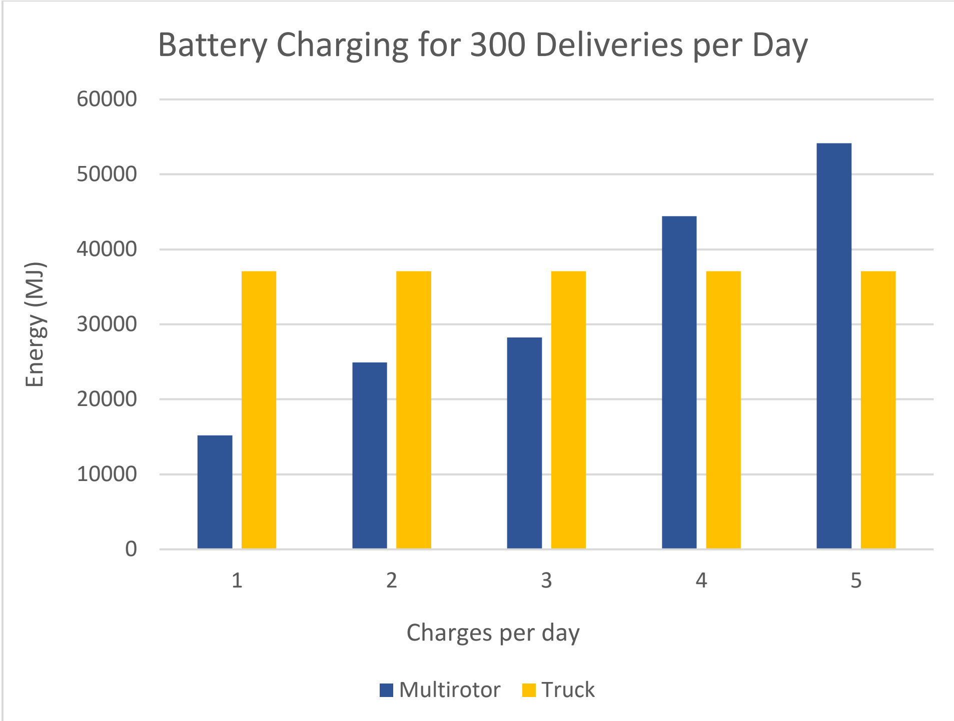

Figure 21 – Comparison of more efficient batteries

The result of more efficient batteries that do not need to be charged as frequently is a decrease in energy use. When the LiPo batteries only need to be charged less than four times per day, they require less energy than to transport packages via truck. This means that each multirotor system would have to deliver 7 packages before charging, or travel about 70 miles.

9.4 Grid Region

Aside from looking at how to change the amount of energy used to power a drone, what type of energy is being used can also be analyzed. The state of New York resides within the Northeast Power Coordinating Council (NPCC) region and has a power grid generated from a majority of nuclear sources and thus is "cleaner" compared to areas like the Midwest Reliability Organization (MRO). From Table 3 in the previous section, the energy mixes of the mentioned two regions are illustrated in Figure 22.

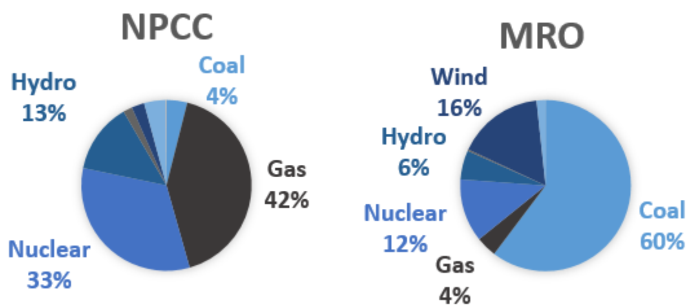

Figure 22 – Energy mix for sample regions

Figure 23 takes these separate regions and looks at the impact of 15 multirotor drones used over 2 years for each energy mix.

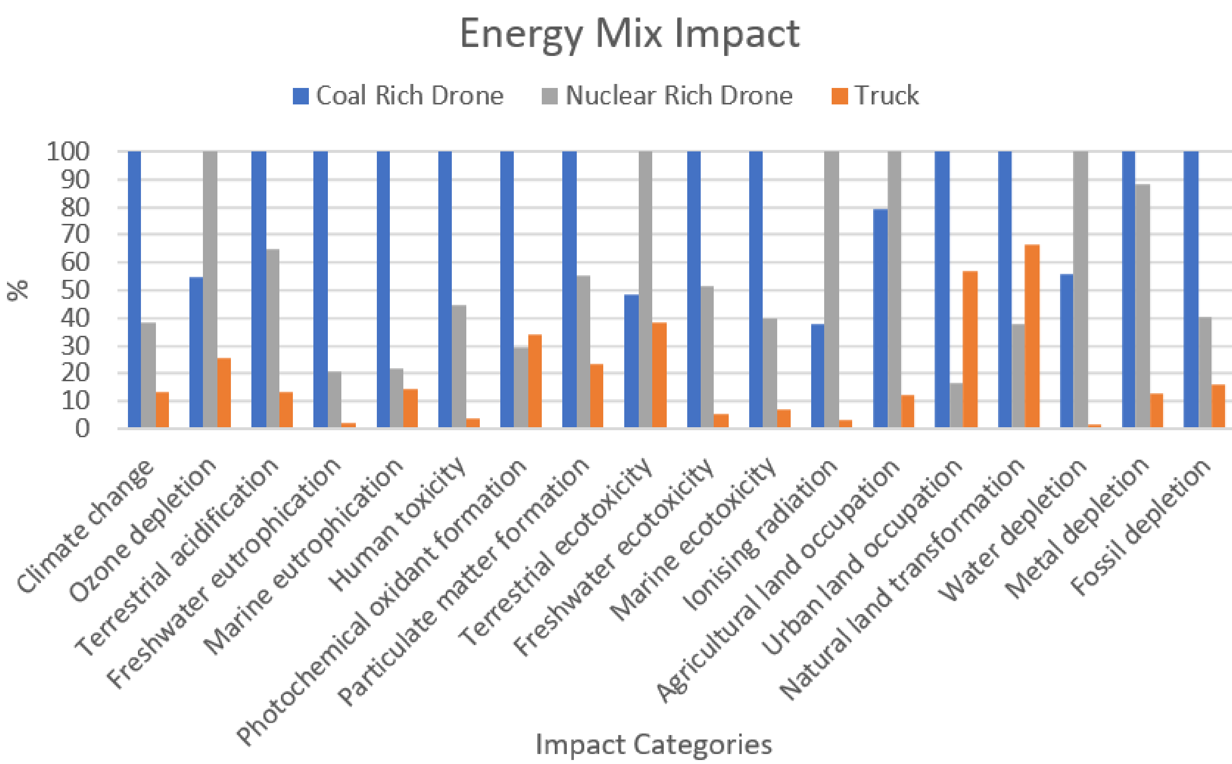

Figure 23 – Energy source implications on results

It is clear that there is a large difference in environmental indicators depending on where the energy comes from. NPCC has a great deal of nuclear power in their energy mix while MRO mostly stems from coal.

9.5 Fixed-wing Drones

The fixed-wing drone did not have as large of an environmental impact as the multirotor drone, as can be expected with their lengthier flight times. Due to their design, the fixed-wing model would not be optimal for delivering packages. The ideal scenario would be a hybrid multirotor and fixed-wing drone. The propellers would assist with takeoff and landing while the fixed-wing design increases travel speeds.

10. Significance & Recommendations

Overall, the use phase has the largest impact, more specifically, the energy used during operation is the most significant. If drone users and commercial industries wish to keep their environmental impact low, they should focus on what kind of energy grid they want to use, depending on what ecological factors they prioritize, and the efficiency of the lithium polymer batteries they buy.

To put this in perspective, there is 3,245 kWh of energy used annually to power 15 multirotor drones operating for 8 hrs a day. In comparison, a household has an annual electricity consumption of 10,812 kWh [EIA, 2016]. The Chevy Volt electric vehicle manufactured by General Motors is estimated to use 2,520 kWh of energy annually [AFDC, 2017].

Structure typically associated with life cycle assessments is not always optimal for determining the impact of a displaced technology. It is difficult to analyze how UAVs might replace, or supplement, a truck and the effect this has on the environment holistically. Also, there are the differences in route traversed and weather impacts. A truck drives on a paved road that needs maintenance and construction. There is also traffic that contributes to the route time and emissions. Drones, on the other hand, are able to fly a straight path to their destination without pause. UAVs are not able to fly in bad weather conditions though such as heavy rain or snow. Trucks, however, are capable of driving through most weather.

This study models a low-level manufacturing system that is mainly made up of manual assembly. If scaled up, there would be an increase in industrial applications and energy use for product assembly. At a greater scale, there would be more automation which may result in different ecological results for the production phase.

This model is highly simplified for more general baselining of Unmanned Aerial Vehicles. The optics is the most abridged component of this study because there is such a large variety of brands and quality in sensors. This is highly dependent on the needs of the user but can reach very complicated arrangements. The energy draw from a larger, more advanced sensor could be a lot higher and have more of an impact on flight time and therefore the environmental impact overall.

This model is only applicable in the United States in its current technological state. Results are relevant for only a short time frame. As energy mixes change among the states, there is a large reflection on this models' ecological impacts. There is also a level of inherent uncertainty surrounding this model in general. Uncertainty regarding data inputs, parameter assumptions, and model representativeness give room for interpretation.

11. Future Work

Further sensitivity analysis is needed to determine the most environmentally-friendly method of delivery. A couple recommend areas for additional research include further drone composition analysis, geographical impact based on location, and different use scenarios. This study is one of many applications of a drone. There are many different uses that require significantly different functional units and displace different operations and machines.

Solar powered drones are in the near future. Research is being done on solar panel fixed-wing drones by do-it-yourself (DIY) hobbyists [UnmannedTech, 2016] and well-known companies like Facebook [Hern, 2015]. Having a drone that is able to collect renewable energy would hypothetically alter how these systems impact the environment. Wirelessly powered drones are also under development. This technology uses cell-tower-type networks to power drones in flight without having to land [GET, 2016].

Something that requires more research as well is to look into exactly how much power is needed to lift and move these systems in different conditions. Currently the battery and power needs of each drone is somewhat approximated. To truly optimize these flights, the total amount of power needed to lift the drones is required. This varies per drone, sensor composition, and other attachments.

An interesting avenue to explore is also how path of travel affects the drones and trucks differently. Trucks are clearly constrained to whatever road paths are pre-made. Drones do not require this costly network of pavement, taking the straight-line approach to their destination, provided they are allowed to travel in that airspace.

Electric vehicles would also be a very interesting technology to explore in an LCA compared to drones. Many people are looking to moving towards electric, or battery-powered, vehicles in the future, including the delivery industry. This technology is rapidly progressing and may make leaps and bounds in the next 20 years, requiring a re-analysis of this study at that time.

Something left out of this study that would be interesting to incorporate is a cost analysis. Industries are driven by economics and looking at how the environmental risks coincide with cost factors would be valuable.

12. Conclusion

This study aims to identify environmental impacts from the analytical model of a general Unmanned Aerial Vehicle of the commercial sector. The manufacturing and operational phases were analyzed and the implications of employing UAV technology to replace or supplement delivery vehicles are highly dependent on location. The energy mix used plays the largest role in determining which ecological impacts are most relevant. The manufacturing of the electronic components and batteries produced the largest impact for a single drone, disregarding the use phase.

LCA modeling did not always properly represent the scope of this study. In particular, when analyzing the displacement of one technology by another the relationship is complicated. The capabilities of one drone does not replace the capabilities of one delivery truck. The model is dependent upon intended use as well as additional potential to complete other activities such as automation, object detection and avoidance, and other factors. Software development is not a factor that can be modeled in SimaPro easily so this also caused inaccuracies.

This study has filled in some of the knowledge gaps regarding the life cycle of Unmanned Aerial Vehicles. The results of this research provide a baseline of environmental impact for UAV technology. It illustrates that the most important factor for businesses to consider, from an ecological perspective, is the use phase of drones when compared to delivery vehicles. This may differ depending on the intended use of the UAV. This model could be improved to represent a scaled-up, industry specific drone. Manufacturing processes for UAV assembly could be more automated instead of manual which would change energy use for the production phase. Sensor modeling could be relevant to the particular type being used as well.

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14. Supplemental Material

As it is, the United States is falling behind in drone research and development due to restricting oversight by the FAA. Other nations have been testing UAV technology long before the United States. Countries such as the UK, Sweden, France, Japan, New Zealand, and South Africa are in the forefront of passing more progressive regulations allowing the use of commercial drones [MacErlean, 2015]. China is dominating the commercial drone industry with the company DJI, followed closely by France.

14.1 Exemptions

Although unregistered operations are illegal in the U.S., Section 333 of the FAA Modernization and Reform Act of 2012 (FMRA) can grant certification for UAVs to operate within the National Airspace System (NAS) on a case-by-case basis. The FAA makes public which companies are granted exemptions and records the operational purposes of each drone. Figure 24 illustrates the representative categories that were applied for using Section 333 exemption by UAV companies to date.

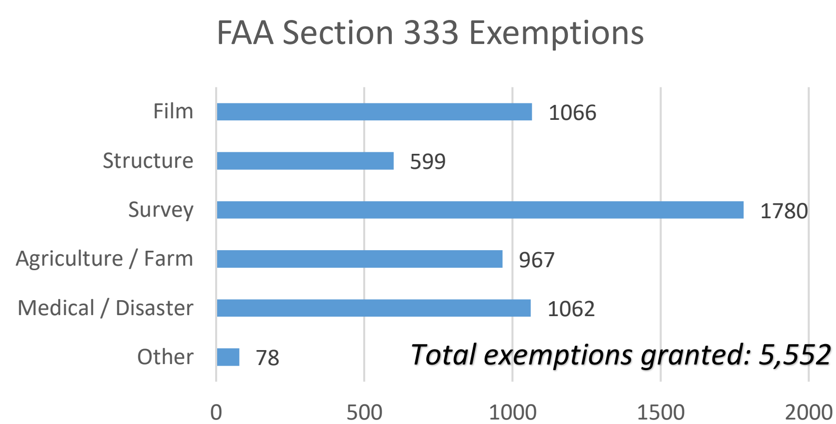

Figure 24 - Drone use chart filtered by Operation/Mission [FAA, 2016]
**Many businesses entered multiple operations/missions*

A few of the companies taking advantage of these federal exemptions include Amazon, Microsoft, Google, and Apple. Granted exemption on October 29, 2015, Amazon was approved for "outdoor testing research and development for Prime Air." Microsoft was approved on April 7, 2016, for "aerial photography and videography for advertising, closed-set motion picture filming and use in software." Google applied for "aerial data collection, including research and development related to aerial delivery with UAS" and was approved on October 29, 2015. Lastly, Apple was granted permission by the FAA on February 4, 2016, to begin "data collection, photography, and videography." [FAA, 2016]

14.2 Areas of Concern

First and foremost, there is the issue of security and potential threat of terrorism, that these machines could be easily hacked and used as a weapon for stealing privacy information and consumer data, transporting illegal contraband [Bamburry, 2015], or even exposing information of classified sites or secrets [Choi-Fitzpatrick, 2016].

Another concern is traffic safety: what are the airline issues this causes and risks to public safety? There are numerous cases where drones have crash landed and hurt innocent bystanders. In the Democratic Republic of Congo, a crash-landing drone resulted in death of civilian on October 3 2009 [Franchi, 2009]. In Incheon, South Korea, a drone crashed into a control truck killing a company engineer and injuring two remote pilots on 10 May 2012 after GPS was lost [Marks, 2012]. Various civil cases have risen where property owners are displeased with the presence of a drone near their land and attempt to shoot it down [T&D Staff Report, 2015]. In all these instances there is a huge list of potential issues: explosions, fires, crashes, distracted drivers, dropped payloads, component failure, pilot error, signal interference, design flaw, environmental forces, un-seen aerial collision, and more.

Although these problems are relatively the same for manned aircraft, the real danger is in the high volume of drones and airspace congestion that stem from the low cost. There are likely to be more points-of-failure, less quality control, lower development software, more inexperienced pilots, and more frequent lapses in control [Moses, 2014].

Legislation and regulatory changes are ongoing but are behind the technology, so have been unable to address many of these issues [Loh, 2009]. The Federal Aviation Administration [FAA, 2016] designates drones be limited to a max speed of 100 mph, max weight of 55 lbs, max altitude of 500 ft, daylight flight only, and always be visible by the operator, who must be at least seventeen and have passed operating certificate tests.

There are currently over 800 acknowledged testing centers, such as SkyOp in Canandaigua, NY, that administer the exams. Anyone who is flying a drone for purposes other than hobby or recreation needs certification. The exam is a 60-question multiple choice exam. Applicants need a 70% score on the exam to pass. Questions are broken down into the following categories: regulation, airspace classification and operating requirements, weather, loading and performance, and operations. Some form of government issued identification is necessary to take the exam as well as a $150 fee. For those persons who already have their pilot license, online remote training is available. Retests are required every 24 months after passing the exam [Pitre, 2016].

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