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Advances in Climate Change Research 9 (2018) 201−207

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Analysis of environmental impacts of drone delivery on an online shopping system

Jarotwan KOIWANIT

Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand

Received 2 April 2018; revised 30 August 2018; accepted 13 September 2018
Available online 19 September 2018

Abstract

In rural areas, drones are designed to replace road deliveries so as to overcome infrastructure challenges; though drones notably consume less fuel and consequently have a smaller impact on the environment, their full life cycle assessment should still be evaluated to comprehensively understand their environmental impact. This study presents a life cycle assessment study on drone delivery in Thailand using CML2001, the life cycle impact assessment (LCIA) method, to convert life cycle inventory data into environmental impacts. The observed results show that an online shopping system using drone delivery is one of the most environmentally friendly transportation options throughout a wide range of scenarios. However, the parts production contributed to significant impacts on environmental issues while the drone operation showed the least impact to all impact categories. The dominant contributors to global warming, abiotic depletion (ADP elements and fossil), acidification air, eutrophication, ozone layer depletion, and photochemical ozone creation impact categories were the coal mining and electricity generating station operation. However, the carbon fibers and the battery, are the main contributors to other impact categories, which include the human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, and terrestric ecotoxicity.

Keywords: LCA; GHG emissions; CML2001; Online shopping; Drone delivery

1. Introduction

With the advent of the internet and increasingly challenging competition in the dynamic business world of today, the online shopping system in Thailand has accelerated to a point where the Thai e-commerce market is expected to triple in growth, from THB47 billion in 2015 to THB139 billion in 2020 (Chan, 2016). New transportation technologies have been introduced to serve customers' requirements, save time and money, and deliver better information while providing companies' high sale numbers and supporting their environmentally friendly programs (Shrivastava, 2013). Transportation is considered as one of the main contributors to CO_2 emissions which contribute to greenhouse gas (GHG) emissions and has posed a serious impact to natural systems (IPCC, 2014; Koiwanit et al., 2014a). Because of traffic congestion in urban areas in Thailand, transportation was named as the second largest source of CO_2 emissions emitted into the air (Mangmeechai, 2016). Even though there is not much traffic congestion in rural areas in Thailand, road infrastructure poses a challenge to retailers in completing each delivery. Unmanned aerial vehicles (UAVs) or drones have been introduced and announced alongside the successes of online shopping systems by a number of companies, such as Amazon, DHL, Google, UPS, etc (Stolaroff, 2014; Heutger and Kückelhaus, 2014; CBC News, 2013; Davidson, 2013). According to DHL, 2014, electrical drones appear to be the most promising type of drone within short distances for online shopping systems even though their use cases are still in the early stages. The carbon footprint calculation of the U.S. online shopping system using different delivery options, which include cars, buses, parcel carriers, road trucks, and airplanes, have been evaluated together along

E-mail address: jarotwan.ko@kmitl.ac.th.

Peer review under responsibility of National Climate Center (China Meteorological Administration).

https://doi.org/10.1016/j.accre.2018.09.001

with electricity generation, the consumption of natural gas, and packaging materials. GWP was evaluated via the production of Li-ion batteries for electric vehicles. The power, energy and capabilities of Li-ion batteries for different passenger cars were also summarized (Miller, 2015). Belmonte et al. (2017) evaluated the GWP using LCA through energy-storage systems on battery-based mobile systems. In contrast to their studies on online shopping systems and energy-storage systems, this study attempts to estimate the environmental impacts of drone deliveries as there have been very limited studies on the creation of their database and their impact on the environment. This study is a cradle-to-gate study focusing mainly on culminating in the creation of a database for drone delivery in Chiang Mai, Thailand, using the LCA methodology. GHG emissions will not only be evaluated, but also other associated emissions of the drone delivery system.

2. Methodology: LCA study of drone delivery services

2.1. Goal and scope definition

This study aims to illustrate the environmental impacts of a drone delivery system in Chiang Mai, Thailand. The home delivery system in rural areas in Chiang Mai, Thailand was chosen since the city is the largest city in northern Thailand, providing a significant increase in its economic growth while still containing rural settlements. As a result, this city was used as the case study.

Again, the study takes a cradle-to-gate approach, starting from the coal mining, electrical generating station operations, drone raw materials, drone productions, and drone use phase.

2.2. Functional unit

The functional unit of this study is chosen as one package delivered per kilometer. This is a functional unit for comparing different forms of transportation that aim to serve home-delivery services. This unit allows significant comparisons to be made since other transportation systems consume different amounts of energy to produce and operate compared to drones but provide the same service within the same distances (Koiwanit, 2015).

2.3. System boundaries

This study is a cradle to gate study that takes into account resource extraction to produce drone, fuel, electricity, and resource depletion through the drone use phase. The system boundary defines the unit processes to be included in the system (Koiwanit, 2015). The system boundary of the drone is shown in Fig. 1.

2.3.1. Temporal and geographical boundaries

The lifespan in this study is assumed to be 5000 h which will be around 250,000 km using the experts' estimates based on drone operation. This is because the major components of vehicles tend to last around 12 years depending on maintenance and economic conditions. However, it is possible that vehicles will be able to operate more than their designed lifespans (Koiwanit, 2015). The processes and data included in the system boundaries come from Thailand, other Asian countries, the U.S., and worldwide (Zhou et al., 2014). The efficiency and specification of the drone delivery in this study can be used in Chiang Mai which has hills in rural areas; as a result, the data from Thailand is for generating the specification of the drone system. However, the parts production is from different countries (Table 1).

2.3.2. Technological boundaries

This study evaluates drone delivery services and their emission impacts. One system in particular is analyzed, which is the drone delivery system using Li-ion battery as a source of energy.

3. Life cycle inventory data quality, sources, and assumptions

In this study, because of data limitation, the LCI data of drone composition by material type comes mainly from experts' estimates. The majority of the data used in this study is specific to Thailand. The assumptions about emissions emitted from the drone delivery processes are mainly derived from the

Table 1
The main parts of the drone delivery system and their references.

Dataset	Reference	Country/Region
Drone frame	City of Toronto (www1.toronto.ca)	Canada
Servo motor	IVL Swedish Environmental Research Institute and EEA (www.ivl.se)	Sweden
Propeller	EEA (webcache.googleusercontent.com)	Europe
Electronic speed control (ECS)	U.S. EPA (www3.epa.gov)	U.S.
Battery	Kang et al., 2013 (pubs.acs.org)	U.S.
Cargo box using carbon fibers	Liddell et al. (2016), Jennings (2015), Harper International (www.harperintl.com)	U.S.
Parts production transportation (100 km)	Ecoinvent	Europe, China
Drone use phase	Wang (2016) (spectrum.ieee.org), the experts' estimates	U.S., Thailand

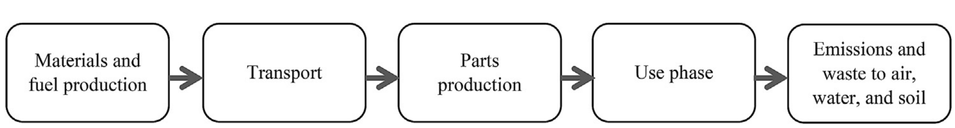

Fig. 1. System boundaries for drone delivery system.

EEA (2009) and the IVL Swedish Environmental Research Institute (SERI, 2017). The main parts of the drone delivery system and their references are shown in Table 1. Because of the data absence for conducting a study of the whole life cycle of the drone delivery system in Thailand together with the limitation of drone site-specific data sources, information from many sources was drawn (Koiwanit et al., 2014b). These sources include:

1) City of Toronto (www1.toronto.ca),
2) IVL Swedish Environmental Research Institute (www.ivl.se),
3) European Environment Agency (EEA) (www.eea.europa.eu),
4) U.S. Environmental Protection Agency (U.S. EPA) (www3.epa.gov),
5) Harper International (www.harperintl.com).

The drone specification and its key parameters are listed in Tables 2 and 3, respectively.

4. Model description

In rural transportation issues regarding the movement of retail goods, trucking companies have been providing freight transportation services; consequently, a truck is considered as one of the most frequently vehicles used which serve customers' shipping needs (IL, 2015). The energy use for the truck is from the combustion of gasoline refined from crude oil and this results in an increase in emissions emitted into the air. Trucks carrying packages for delivery require many more miles than drone delivery which is able to travel on individual direct routes (Stolaroff, 2014). As trucks face the increasing challenge of transporting freight across remote supply chain, this brings about alternative transportation methods, one of these being drone delivery systems. This is because the system is not only inexpensive and easily available but can also perform complex and dangerous tasks (Rao et al., 2016).

This study develops a drone model and evaluates its environmental impacts to see its environmental feasibility of replacing traditional freight transportation services using other transportation modes. There are two main types of engines used in non-military drones which include 1) the electric engine and 2) the internal-combustion engine. The internal-combustion engine is best used for longer distance flights but is expensive and noisy (Heutger and Kückelhaus, 2014). Unlike the internal-combustion engine, the electric engine was chosen since it can be operated without much noise, it is inexpensive to charge its battery, and is more environmentally friendly. As a result, it appears to be the most promising choice for application in the logistics industry (Heutger and Kückelhaus, 2014). Even though the limitation of this engine type lays in its limited battery capacity, the battery-powered drones can be recharged when they are docked (Heutger and Kückelhaus, 2014; McFarland, 2017). In this study, several assumptions have been investigated, which include 1) drone energy use, 2) average number of packages, 3) average weight limit, and 4) the average distance to be traveled. Since drones are designed for use in different environments and they vary in size depending on the number of packages and their total weight, this results in different energy usages and distances to be traveled. The basic designs in this study are as follows:

- Drones can last up to 30 min (Pandit and Poojari, 2014)
- Drones can carry products up to 5 kg
- Drones' cargo box dimension is 30.48 cm × 30.48 cm × 25.4 cm

Table 2
Drone specification (modified from www.dji.com).

Element	Specification
Diagonal wheelbase	1133 mm
Dimensions	1668 mm × 1518 mm × 727 mm with propellers, frame arms and GPS mount unfolded (including landing gear) 437 mm × 402 mm × 553 mm with propellers, frame arms and GPS mount folded (excluding landing gear)
Weight (with six TB47S batteries)	9.5 kg
Weight (with six TB48S batteries)	10 kg
Max takeoff weight recommended	15.5 kg (drone together with delivered goods)
Hovering accuracy (P-GPS)	Vertical: ±0.5 m, Horizontal: ±1.5 m
Max wind resistance	8 m s^{-1}
Max ascent speed	5 m s^{-1}
Max descent speed	3 m s^{-1}
Max service ceiling above sea level	2170R propellers: 2500 m 2195 propellers: 4500 m
Max speed	65 km h^{-1} (no wind)
Hovering time (with six TB47S batteries)	No payload: 32 min, 6 kg Payload: 16 min
Hovering time (with six TB48S batteries)	No payload: 38 min, 5.5 kg Payload: 18 min
Flight control system	A3 Pro
Propulsion system	Motor model: DJI 6010 Propeller model: DJI 2170R
Retractable landing gear	Standard
Operating temperature	−10 to 40 °C
Energy use per package per kilometer	0.093 MJ

5. Life cycle impact assessment (LCIA)

This study aims to determine the hotspots throughout the full life cycle of the drone delivery system. Towards this aim CML2001 was chosen, as this method is well-established, comprehensive, and commonly used. The CML2001 method has been acceptably used by the Thailand Environment Institute (TEI) and the Thai government (Lohsomboon et al., 2004; Wankanapon et al., 2013). Consequently, we can deem CML2001 to be best suited for this study. CML2001 was developed by the Institute of Environmental Sciences at Leiden University in the Netherlands, Guinée, 2002). It is a midpoint-

Table 3
Key parameters of the studied drone delivery.

Products of combustion	Important information	Details
Frame	Weight (with six batteries)	10 kg
	Materials used	Carbon fiber = 85% Plastic = 10% Aluminum = 5%
Servo motor	Motor model	DJI 6010 (E2000 pro)
	Max thrust	5100 g per rotor (50 V, sea level)
	Recommended battery	12S LiPo
	Recommended takeoff weight	1800−2500 g per rotor (sea level)
	Powertrain cable length	750 mm
	Compatible arm tube outer diameter	28 mm
	Stator size	60 mm × 10 mm
	KV	130 rpm V^{-1}
	Weight	230 g
	Materials used	Steel = 55% Copper = 35% Magnet = 10%
Propeller	Propeller model	DJI 2170R
	Diameter/Thread pitch	533 mm × 178 mm
	Weight (single propeller)	58 g
	Material used	Plastic
ECS	Max allowable voltage	52.2 V
	Max allowable current (continuous)	25 A
	Max peak current (3 s)	40 A
	PWM input signal level	3.3/5 V compatible
	Operating pulse width	1120−1920 μs
	Signal frequency	30−450 Hz
	Battery	12S LiPo
	Dimensions	85 mm × 44 mm × 18 mm
	Cable length	750 mm
	Weight (without cables)	55 g
	Weight (with cables)	90 g
	Materials used	Electric device e.g. resistor, transistor, CU, etc.
Battery (36 cells)	Battery model	TB48S
	Capacity	5700 mAh per 6 cells
	Voltage	22.8 V per 6 cells
	Battery type	LiPo 6S (6 cells)
	Energy use (for delivery)	129.96 W h per 6 cells
	Net weight	680 g per 6 cells
	Operating temperature	−10 to 40 °C
	Max charging power	180 W per 6 cells
Box	Dimension	102 mm × 102 mm × 2.4 mm
	Weight	181.437 g
	Materials used	Carbon fibers = 100%

oriented method that includes characterization and normalization in the impact assessment process. In addition, GaBi 7, an LCA software product of PE International, Germany, is used in this study as this is the most frequently used software that provides a full range of analytical LCA tools (Koiwanit et al., 2014a, 2014b; Koiwanit, 2015). The study takes into account all associated emissions, wastes, and resource and energy consumption amounts during the life cycle stages using CML2001 methodology. The main focus of this research is on all 11 environmental impact categories, which include global warming potential (GWP), abiotic depletion (ADP elements), abiotic depletion (ADP fossil), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAEP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAEP), ozone layer depletion potential (OLDP), photochemical ozone creation potential (POCP), and terrestric ecotoxicity potential (TETP).

6. Results

The LCIA results from the CML2001 methodology are shown in detail by impact category and summarized in the following sections.

6.1. Global warming potential (GWP)

The environmental impact in terms of global warming potential is 0.079 kg CO_2-eq in the drone delivery system. The impact was primarily due to parts production, which accounted for 99.2% of the impact. CO_2, CH_4, and N_2O were the main substances that contributed to global warming, which accounted for 80.88%, 2.75%, and 0.89%, respectively.

6.2. Abiotic depletion (ADP elements)

The total abiotic depletion impact is 1.67×10^{-8} kg SO_2-eq for the drone delivery system. Part production and part transportation contributed 93.50% and 6.44%, respectively to the impact on the abiotic depletion (ADP elements) category. The main substances that contributed to the non-cancer air category include copper (Cu), silver (Ag), lithium (Li), and lead (Pb), which accounted for 20.47%, 17.67%, 15.72%, and 15.37%, respectively of the impact in this category.

6.3. Abiotic depletion (ADP fossil)

There is a total number in the environmental impact category of abiotic depletion considering ADP fossil of 5.16×10^{-5} MJ in the drone delivery system. In the impact to the abiotic depletion, around 98.12% of the contribution to this category was generated from parts operation and 1.83% from the parts transportation. The main substances that contributed to the abiotic depletion were lignite, hard coal, and natural gas, which accounted for 43.62%, 33.39%, and 18.40%, respectively. As the emissions were from the operation of the electric generating station, renewable energy can be used to reduce this impact category.

6.4. Acidification potential (AP)

The environmental outcome in the acidification air impact category is 5.16×10^{-5} kg SO_2-eq for the online shopping system using a drone. In this impact category, 98.20% of the contribution was derived from parts production and 1.78% was from the parts transportation, and 0.02% from the drone operation. The dominant contributors to the acidification air were SO_2, NO_x, and H_2S, which accounted for 51.32%, 34.91%, and 7.86%, of the contribution to this impact category, respectively.

6.5. Eutrophication potential (EP)

The CML2001 method represents eutrophication in different media (soil, air, or water) as one category of nutrient enrichment potential impact. The total result of this impact category is 8.65×10^{-6} kg Phosphate-eq. This indicated that the potential for eutrophication was derived mainly by parts production and transportation, which accounted for 93.20% and 6.97% of the effect, respectively. The main contributors in the eutrophication air impact category calculated per 1-km traveled were from NO_x, NO_3^-, nitrogen organic bound, and N_2O, which accounted for 57.18%, 8.99%, 6.40%, and 4.82%, of the contribution in this impact category, respectively.

6.6. Freshwater aquatic ecotoxicity potential (FAEP)

The results from the CML2001 method indicated that the total impact is 1287.28 kg DCB-eq. The main processes that contributed to the freshwater aquatic ecotoxicity impact category was parts production, which accounted for almost 100%. There are many substances that cause freshwater aquatic ecotoxicity; some examples include chemical Cu, Co, Ni and Cd. These accounted for 43.15%, 23.3%, 19.6%, and 8.01%, respectively.

6.7. Human toxicity potential (HTP)

The drone delivery system shows the total impact in human toxicity potential which is 5.28×10^{-5} kg DCB-eq. It was observed that parts production contributed almost 100% to the human toxicity category. NO_x, NO, and NO_2 were the main contributors to the category of eutrophication, which accounted for 48.62%, 42.65%, and 2.22%, of the contribution in this impact category respectively. The parts production was the source of heavy metals. As, Cd, Ni and Cu emissions were mainly emitted from carbon fibers and Li-ion productions.

6.8. Marine aquatic ecotoxicity potential (MAEP)

In the marine aquatic ecotoxicity potential impact category, the total impact is 6.9×10^{6} kg DCB-eq. Parts production processes contributed almost 100%. Heavy metals, which include Cu, Co, Ni were the main substances that contributed to marine aquatic ecotoxicity, which accounted for 32.43%, 31.09%, and 25.94%, respectively.

6.9. Ozone layer depletion potential (OLDP)

The total potential for ozone layer depletion in the drone delivery system were 2.14×10^{-12} kg R11-eq. This number was derived from parts production and transportation, which accounted for 98.17% and 1.83% of the total, respectively. The main substances that caused ozone layer depletion included dichlorotetrafluoroethane (R114) and chlorodifluoromethane (R22), which accounted for 97.03% and 2.97%, respectively, of the impact in this category.

6.10. Photochemical ozone creation potential (POCP)

The online shopping system using a drone for delivery showed a total photochemical ozone creation potential impact of 3.82×10^{-6} kg Ethene-eq. Production and transportation of the drone for delivery contributed 98.22% and 1.78% respectively to the photochemical ozone creation potential impact category. NMVOC, SO_2, and NO_x accounted for 29.78%, 27.61%, and 26.32%, respectively of the contribution in this impact category.

6.11. Terrestric ecotoxicity potential (TEP)

The total number in the environmental impact category of terrestric ecotoxicity was 3.85×10^{3} kg DCB-eq in the drone delivery system. This impact was due to the emissions mainly derived from the parts operations, which accounted for almost 100%. The dominant contributors to the terrestric ecotoxicity impact category were As, Cr, and Pb, which accounted for 52.8%, 40.8%, and 2.1%, of the contribution in this impact category respectively.

7. Discussion

The results from the LCA of the drone delivery system shows that the dominant contributor to all environmental impact categories is the parts operation. Parts operation can be divided into three main categories, which include coal mining, electrical generating station operation, and parts production. Coal mining and electricity generating station operation were the main contributors to global warming, abiotic depletion (ADP elements and fossil), acidification air, eutrophication, ozone layer depletion, and photochemical ozone creation impact categories. Parts production, especially the carbon fibers production which is the raw material for the cargo box and Li-ion production which is the main input for the battery, is the main contributor to the human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, and terrestric ecotoxicity impact categories. Drone operation shows the least impact to all impact categories as seen in Fig. 2. According to Park et al. (2018), the global warming per 1-km delivery by drone was 0.004 kg CO_2-eq. However, the global warming potential from this study was 0.079 kg CO_2-eq, which shows higher impact than that of (Park et al., 2018). In addition, the global warming potential of 1 km traveled by motorcycle and electric motor was 0.028 and 0.018 kg CO_2-eq, respectively (Park et al., 2018). This shows that drone delivery for online shopping systems is environmentally friendly compared to other delivery systems especially when they are under operation (Gulden, 2017). However, drones are suitable for short trips with light-weight items while ground vehicles are suitable for carrying heavier products in long distance (Tseng et al., 2017).

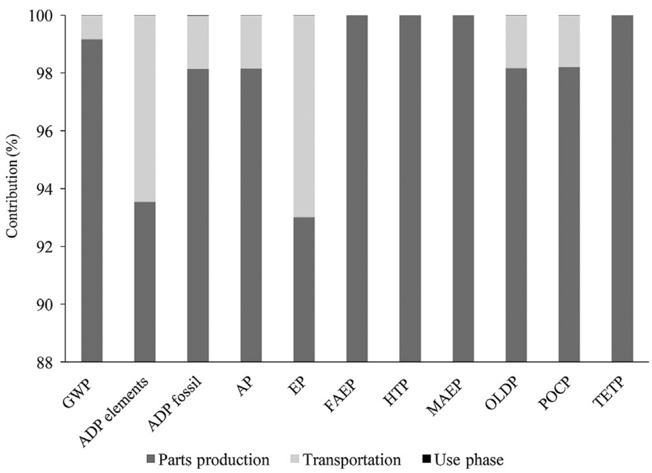

Fig. 2. Contributions of each process toward all impact categories.

8. Conclusions

This study proposes an alternative implementation of online shopping delivery systems in which customers can get their groceries at their doorstep within a short period of time. The environmental performance of the drone delivery system was analyzed and the results were generated using CML2001. The results showed that emissions were mainly from parts production, which include coal mining, electrical generating station operation, and parts production while the drone operation showed the least impact to all of the impact categories. The main contributors that caused global warming, abiotic depletion (ADP elements and fossil), acidification air, eutrophication, ozone layer depletion, and photochemical ozone creation include coal mining and electricity generating station operation. The carbon fibers and Li-ion are the main contributors to the human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, and terrestric ecotoxicity impact categories. However, there are still some other raw materials or unavailable data which have not been taken into account which will result in different environmental impacts. In the future, this LCA study should be extended to include other raw materials. In addition, it is recommended that for future work other delivery systems such as trucks or cars should be evaluated to compare their environmental performance with the results of this study. This will show which system is more environmentally friendly.

Acknowledgments

The author is grateful for the financial support from Research Seed Grant for New Lecturer from KMITL Research Fund and the technical support from Mr. Junraprach Petchang, a Chulalongkorn University's graduate student.

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