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CARBON DIOXIDE LIFE CYCLE ASSESSMENT ON URBAN AIR MOBILITY IN CONTEXT OF EMERGENCY MEDICAL SERVICE

Master's Thesis

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Abstract

This thesis presents the development of life cycle assessment framework, which includes a series of conceptual models, to evaluate the end-to-end environmental impacts of Urban Air Mobility (UAM) systems, with a specific focus on their application in Emergency Medical Services (EMS) scenarios. The LCA study examines two types of UAM technologies: drones for the delivery of medical supplies and medium-sized electric Vertical Take-off and Landing (eVTOL) aircraft for the transport of medical personnel or patients. The proposed LCA assessment framework incorporates sensitivity analysis modules to account for the uncertainties prevalent in the respective domains.

The carbon dioxide emissions in the UAM ecosystem are largely due to the construction and operation of supporting ground infrastructure, as well as the production and operation of unmanned aerial systems, as underscored by this thesis. The analysis reveals that motor production generates the highest environmental impact, while battery-related impacts are uncertain and influenced by flight frequency. Additionally, the study emphasizes the importance of local grid intensity and weather conditions in determining the overall emissions associated with UAM operations.

As UAM technologies continue to mature, it is advocated that additional scenario-based and network-level evaluations be carried out. The developed framework in this thesis holds potential for enhancement through improvements in data quality, thereby contributing to a more robust understanding of the environmental implications of UAM in EMS contexts.

Keywords Urban Air Mobility, Life Cycle Assessment, Emergency Medical Services, Sustainability, Carbon Dioxide

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Table of Abbreviations

Abbreviation	Full term
AEDs	Automated External Defibrillators
Air EMS	Air Emergency Medical Service
ATM	Air Traffic Management
B2B	Business-to-Business
BIPV	Building-Integrated Photovoltaics
CMP	Certified Minimum Performance
CO_2	Carbon Dioxide
DVRP	Dynamic Vehicle Routing Problem
EASA	European Union Aviation Safety Agency
EEA	European Environment Agency
EMS	Emergency Medical Services
EU	European Union
eVTOL	electric Vertical Takeoff and Landing
FAA	U.S. Federal Aviation Administration
FATO	Final Approach and Take-Off area
GHG	Green House Gas
HEMS	Helicopter Emergency Medical Services
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IoT	Internet of Things
L/D	Lift-to-drag ratio
LCA	Life cycle assessment

LiPo	Lithium-Polymer
MATSim	Multi-Agent Transport Simulation
MRO	Maintenance, Repair, and Overhaul
PL	Power loading
SoS	System-of-Systems
sUAS	small Unmanned Aerial Systems
TLOF	Touchdown and Lift-Off Area
TRL	Technology Readiness Level
UAM	Urban Air Mobility
UAS	Unmanned Aerial Systems
UML	UAM Maturity Levels
VLL airspace	Very Low-Level airspace

1 Introduction

1.1 Background and Research Gap

Greenhouse gas (GHG) emissions serve as the primary driving force behind anthropogenic climate change. Transportation is the second-largest source of GHG emissions globally energy-related GHG emissions, responsible for around 25% of total GHG emissions in the European Union (EU) (United Nations Environment Programme, 2022). According to the European Commission, the European Climate Law sets the ambitious goal of reducing the net GHG emissions by at least 55% compared to 1990's level by 2030 and realize the ultimate net zero GHG emission target by 2050 (European Climate Law, 2021). However, reported by Centre for Nature and Climate, even without considering Covid's negative impacts on the transportation sector, compared with 1990's level, the GHG emissions decreased in every sector, except transportation (Masterson, 2022).

Carbon Dioxide (CO_2) is the most ubiquitous emitted GHG across various industries (European Environment Agency, 2020). Major CO_2 emissions in the transportation sector primarily stem from the combustion of fossil fuels. However, improvements in fuel efficiency have been insufficient to counteract the rising CO_2 emissions due to increased transportation volume (Masterson, 2022). The Jevons Paradox suggests that such efficiency gains may inadvertently result in higher consumption, as resources become more economically viable. In the case of transportation, advancements in fuel efficiency have been shown to be inadequate to offset the sector's growing CO_2 emissions, as demand continues to outpace sustainability improvements. Therefore, addressing the Jevons Paradox necessitates comprehensive strategies to reduce CO_2 emissions in the transportation sector, focusing on both enhancing efficiency and managing the growing demand for transportation services.

To offset the impact of growing demand for transportation services and meanwhile achieve the goal of carbon neutrality by 2050, the possible solutions include ongoing advancements in sustainable energy sources, enhancing fuel efficiency in an economically viable manner, and increasing the adoption of vehicles powered by more sustainable energy, such as Electric Vehicles (EV), hydrogen-driven vehicles, and electric Unmanned Aerial Systems (UAS), which includes medium-size electric Vertical Takeoff and Landing (eVTOL) aircraft that could be used to transport passengers and small Unmanned Aerial Systems (sUAS, also called drones) used to transport packages or cargos.

Researchers have conducted extensive investigations into the sustainability concerns and CO_2 emissions associated with UAS operations, as well as the broader Urban Air Mobility (UAM) ecosystem. But the research results vary from one to another. The lack of a unified conclusion underscores the need for further inquiry to elucidate the nuances and trade-offs involved in the adoption and deployment of UAM systems.

Large uncertainties exist in the UAM CO_2 impact assessment. The UAM's carbon footprint not only depends on the vehicle operation systems, but also the energy source used to power the aircraft and other supporting systems. In contrast to conventional fossil fuel-driven transportation modalities, electric UASs generate no tailpipe emissions during flight operations. Nonetheless, it is essential to acknowledge CO_2 emissions resulting from the combustion of fossil fuels or electricity generation processes, which contribute to the overall environmental impact. The 2021 International Energy Agency (IEA) report pointed out that 41% shares of global CO_2 emissions is caused by electricity generation (IEA, 2022). Coal-fired power plants are the main contributor to global CO_2 emissions, releasing approximately 20 times more CO_2 than renewable energy sources such as solar, wind, hydro and geothermal (Planete Energies, 2016). The regional variability in energy mix and policies results in a complicated landscape of CO_2 emissions within the electricity generation sector. For example, in 2018, the carbon intensity of electricity generation in India was 709 g CO_2eq/kWh, which is 2.64 times higher than the average across the EU, which was 269 g CO_2eq/kWh (IEA, 2022). However, this difference is subject to change over time as new technologies and policies are implemented.

In addition to consider the carbon emissions shifted the to the upstream electricity generation power plants (Zhang, 2021), it is worthwhile to explore the sustainability level of the UAS production and the infrastructure construction and implementation. Therefore, Life cycle assessment (LCA) study is perceived as a scientifically rigorous method to provide quantitative evidence and thus present a holistic overview of the sustainability of UAM to stakeholders.

The UAM adoption scenarios let the CO_2 assessment results vary and Emergency Medical service (EMS) has been perceived as the earlier adoption scenario of UAM. The Swedish company Everdrone has utilized UASs to transport defibrillators and medical personnel for life savings (Everdrone, 2022).

Previous studies primarily focused on investigating the sustainability of UAM network planning issues in the context of merchandise package delivery and public transportation modes, while the operations of UASs in EMS scenarios differ from UAS-based last-mile package or passenger delivery. Given the emergency and potentially hazardous situations, in EMS scenarios, flight safety is of the utmost importance, followed by ensuring timely and effective response to patients' needs. UASs must be pre-equipped with essential medical equipment and maintained in a ready-to-deploy state 24 hours a day. While route optimization and operational efficiency are important considerations, they remain secondary to the primary objectives of flight safety. The unique characteristics of UAM in the context of EMS necessitate distinct considerations for sustainability assessment, setting it apart from other scenarios. This merits further exploration and dialogue within the academic community, as understanding these nuances can inform effective policy and practice for integrating UAM into EMS.

1.2 Research Objective and Scope

This thesis research focus is to address the following questions:

- What factors affect the carbon footprints of UAM?
- Is UAM more sustainable than other modes of transportation?
- From the Lifecycle Assessment perspective, how much Carbon Dioxide would be emitted if incorporating Urban Air Mobility into the existing Emergency Medical Services?

The research scope of this thesis is centered on a comprehensive LCA study focusing on the CO_2 emissions associated with the adoption of UAM concepts in EMS scenarios. This thesis aims to illuminate the full spectrum of CO_2 emissions directly attributable to the manufacturing, operation, and end-of-life treatment of UAM vehicles, as well as those associated with necessary background systems - in this thesis, the requisite ground infrastructure.

This thesis offers a holistic understanding of the environmental footprints of UAM within the EMS sector and identifies areas for improvement and potential mitigation strategies. Ultimately, the targeted audience of thesis is not only academics and industry professionals aiming to reduce carbon footprints but also for policymakers who are in the position to make informed decisions about the future of urban transportation.

1.3 Research Methods

This thesis starts from conducting a comprehensive literature review and then develops an integrated LCA methodology specifically designed to conceptually evaluate the lifecycle CO_2 impact associated with UAM concepts. The CO_2 LCA study is conducted by following the standards issued by ISO14040/14044: 2006.

In addition to development of the LCA models, this thesis delves into their practical applications, adopting these models with selected aircrafts in real scenarios and demonstrating the integration of these LCA models, consequently offering a comprehensive CO_2 measurement framework for UAM within the EMS context. Sensitivity analyses modules within the proposed models are conducted to cater for the uncertainties typical in the corresponding domains.

Two UASs, Falcon L and EH216 manufactured by EHang Scandinavia AS (EHang), are selected as proxies for EMS UAS. Falcon L is adopted to evaluate the environmental performance of drones and EH216 is adopted to represent the passenger eVTOL. Since EHang is continuously integrating the configurations of EH216, the specific type applied in this study is EH216SV-A01, but the simplified name, EH216, is used in the following reports.

The data collected for the practical applications these conceptual models are supported by comprehensive CO_2 LCA study results published openly by scientific scholars and data provided by industrial participants, in order to address the primary research objective: obtaining a macro-level perspective on the CO_2 impacts of UAM. The data and figures utilized in this thesis are processed using Python.

This thesis is the Work Package 5.1 deliverable of AiRMOUR project, which is a research and innovation project funded by European Union’s Horizon 2020 under grant agreement No 101006601. A preceding analysis considering the foresight of incorporating EMS as a plausible early use case for UAM was accomplished within the AiRMOUR project’s Work Package 2.1 deliverable (Georgiev, Larrouturou, & Stjernberg, 2021). Subsequently, four distinct use scenarios were delineated and validated as part of the deliverable for AiRMOUR’s Work Package 2.2 (Krivohlavek, 2021). The progression of these work packages has laid the foundation for the research conducted in this thesis.

2 Literature Review

Urban Air Mobility (UAM) is widely accepted as the on-demand and multi-modal mobility which takes advantage of the novel Unmanned Aerial Systems (UAS) and airspace designs to address intra-city air travels. European Union Aviation Safety Agency (EASA) defined UAM as:

UAM is a new safe, secure, and more sustainable air transportation system for passengers and cargo in urban environments, enabled by new technologies and integrated into multimodal transportation systems.

This literature review provides comprehensive background information and critically discussed on the topic of UAM, Life Cycle Assessment (LCA), CO_2 LCA studies on UAM, and CO_2 LCA study on the scaled-up system-level UAM adoption. It also highlights the research gap in LCA studies on UAM in the context of Emergency Medical Services (EMS).

2.1 Life Cycle Assessment and Urban Air Mobility

2.1.1 Carbon Dioxide Life Cycle Assessment

Life Cycle Assessment (LCA) is a rigorous, quantitative methodology that originated in the 1970s to evaluate and quantify the environmental impacts of a product or service over its entire life cycle. LCA study results are normally used by designers, manufacturers, researchers, and policymakers for the robust comparisons between different products or other decision-making processes (Hellweg & Milà i Canals, 2014). The four iterative phases of LCA standardized by the ISO 14040 series depicted in Figure 1 are: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2020).

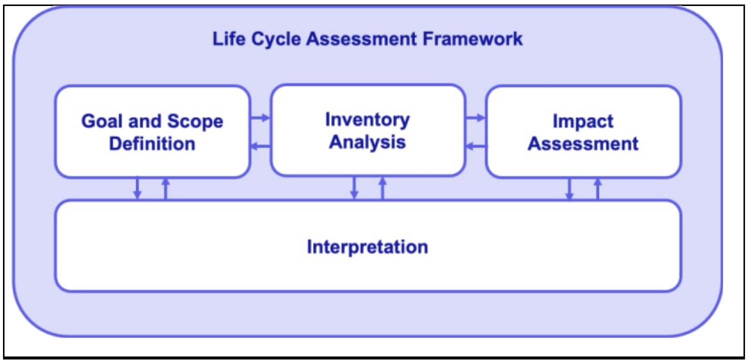


Figure 1. Life cycle assessment framework.

LCA study can be conducted in a Cradle-to-Grave or Cradle-to-Cradle perspective, which encompasses all stages of the life cycle and requires investigations throughout the complete lifespan of a certain product. A Cradle-to-Grave LCA begins with the extraction of raw materials, followed by manufacturing, product usage, and recycling or ultimate disposal at the end of life. Otherwise, LCA can also be studied in a focused manner, such as Cradle-to-Gate, Gate-to-Grave, etc.

In the context of the transportation industry, CO_2 LCA studies may use different terms depending on the product or process being evaluated. For conventional vehicles, one of the most used scopes of the CO_2 LCA is "Well-to-Wheel," which represents the combination of two stages: "Well-to-Tank" and "Tank-to-Wheel." The former accounts for emissions that occur along the fuel or energy supply chain, while the latter considers only the combustion process. Specifically, in the case of electric UASs operating within the context of UAM, the "Well-to-Wheel" stage could also be called as "Battery-to-Propeller" stage, which is associated with the electricity supply chain, which includes losses in transmission, distribution, charging and discharging, and propeller efficiency.

2.1.2 Why Cradle-to-Grave Life Cycle Assessment?

The most common type of LCA studies is retrospective LCA on existing products or services that have been in use for some time and the real data for past is available to support decision-making. Scholars also conducted LCA on emerging technologies like UAM as scientific evidence to prove whether they have environmental advantages over existing technology like cars or vans.

There are multiple compelling reasons to prove that conducting a conceptual Cradle-to-Grave LCA model to evaluate the CO_2 impact of UAM is a necessity. A proactive and strategic approach like LCA to assess environmental impact is essential for maximizing cost efficiencies. Figure 2 delineates how the costs, primarily incurred during the later stages of a product's life cycle, are nonetheless committed during the initial developmental phases. Conceptual modeling the environmental life cycle impact of UAM prior to actual implementation offers the highest potential to save costs in such a complex and dynamic UAM ecosystem (Vajna, 2020). The environmental impact can be evaluated from a holistic perspective with LCA, allowing for the identification of areas where cost savings can be achieved and more informed decision-making.

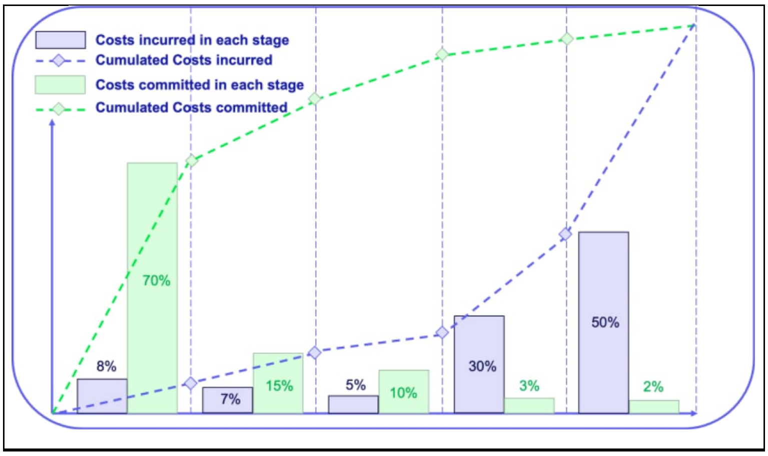


Figure 2. Committed cost versus incurred cost over a product's life cycle (André, 2022).

Furthermore, Cradle-to-Grave LCA is necessary because it provides a comprehensive analysis of the environmental impact of UAM over its entire lifecycle, including the aircraft and power system production, operation, and end-of-life phases. By undertaking an LCA, the carbon footprint of UAM can be determined. Gaining insight into the proportions of CO_2 emissions that are attributable to flight operations, aircraft production and disposal, or other LCA stages within the overall life cycle emissions of UAM respectively would be useful to identify areas where emissions can be reduced and develop strategies to mitigate the environmental impact of UAM.

The upstream emissions during flight operations of UAS are highlighted by literature LCA studies. For fossil-driven vehicles, research indicates that approximately 30% of the lifecycle emissions associated with freight transportation stem from upstream processes, such as fuel production and distribution, while 70% are generated from tailpipe CO_2 emissions (Horvath, 2006). Conversely, electricity powered UASs emit zero tailpipe CO_2, with 100% of emissions attributed to upstream processes, primarily electricity generation. It is important to recognize that upstream electricity production is not entirely emission-free, even in countries with a high proportion of renewable energy sources, such as Norway. The use of fossil fuels in the energy mix inevitably results in some CO_2 emissions during electricity generation. Additionally, it is possible that the disparities in energy consumption due to the varying efficiencies of energy conversion let the emissions related to the assessment of CO_2 emissions generated from electricity-powered UASs more sustainable than the fossil-combusted vehicles. It has been revealed that electric motors exhibit a significantly higher energy conversion efficiency, typically greater than 90%, while internal combustion engines possess a markedly lower efficiency, typically less than 50% (Linquip Team, 2021). Thus, exploring the sustainability of electricity powered UASs compared to other vehicles presents a complex and intriguing challenge due to varying energy conversion efficiencies and the diverse sources of CO_2 emissions.

Besides, previous studies examining the sustainability of UASs have typically focused on Well-to-Wheel stage but excluded the impacts from inventories like UAM infrastructure or the production and disposal of UASs. Bishop et al. recommended to include one additive in the LCA scope when there is no clear evidence that their contribution is less than 1% to the whole (Bishop, Styles, & Lens, 2021). Even though the scientific community has not yet reached a consensus on the most acceptable scope of UAM LCA studies, there are arguments that those inventories have an insubstantial influence on the outcome of the sustainability study on UAM.

LCA Research on the production and disposal stage of UASs could post benefits for exploring sustainable materials or recycling measures to make UAM more sustainable. For example, one of the essential materials of the airframe of a UAS, carbon fiber composites, would generate great environmental impact during the whole lifecycle of UASs. The production of carbon fiber composites does contribute to CO_2 emissions, but the recycling of these materials could mitigate the emission to some extent (Koiwanit, 2018). Identifying the possible impacts from its production and end-of-life processes could motivate the development of the possibly more sustainable approaches to handle UASs from beginning to the end of their lives (Ribeiro & de Oliveira Gomes, 2015). This would contribute to the overall sustainability of the UAM industry, promoting long-term viability while reducing its environmental impact.

2.1.3 Life Cycle Stages

The lifecycle emissions of fossil energy combustion mobilities could be divided into the three cycles: the fuel cycle, the vehicle cycle, and the infrastructure cycle, see Figure 3 (Zhang, 2021). The three cycles could be divided into the three stages of LCA study respectively, which are Sourcing Stage and Production Stage, Operation Stage, and End of Life Stage. The fuel cycle includes the upstream raw material extraction, processing and distribution, and tailpipe use of fuel. The vehicle cycle contains upstream raw material extraction, manufacturing and distribution, vehicle operations and maintenance, and end-of-life disposal or recycling of the vehicles. The infrastructure cycle includes the construction, operation, maintenance, and end-of-life processsing of transportation infrastructures.

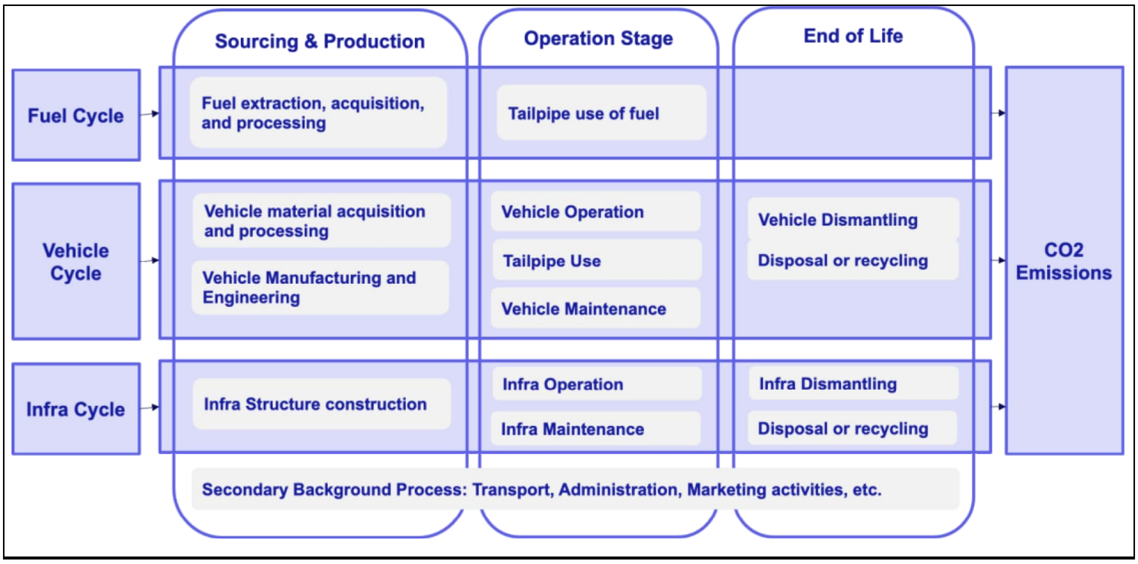


Figure 3. Three cycles and three life cycle stages - fossil fuel energy combustion.

The lifecycle emissions of fuel urban air mobility could just be summarized into one cycle: Recourses and energy cycle. Figure 4 shows the three life cycle stages of the Recourses and energy cycle. The sourcing production stages include the raw material acquisition, processing and manufacturing of the aircraft, power system, and the energy system providing the energy to the power system. If the power system utilized by the UAS is battery, the energy system is electricity. If the UAS is designed with hydrogen-driven power system, the energy system should be hydrogen production system. The Operation Phases are similar with other mobilities, including the aircraft vehicle and infrastructure system operations and maintenance. The end-of-life stage consists of the dismantling of the aircraft and the infrastructure, the disposal or recycling of the airframe, power system, and the energy system.

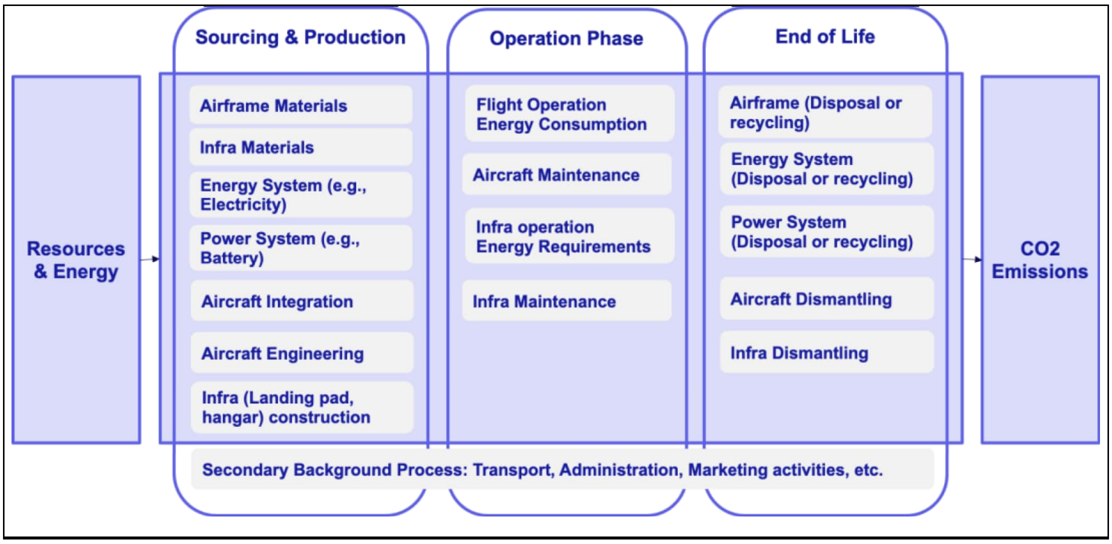


Figure 4. Cycle and three life cycle stages – UAM concepts.

2.1.4 Life Cycle Assessment and Small Unmanned Aerial Systems

In conducting an LCA for UAM systems, a comprehensive and precise description of the system under analysis is crucial. However, varying definitions and operational frameworks presented in different sources complicate the comparison of studies. Additionally, even when a consensus on the system's structure is achieved, the selection of distinct boundaries further exacerbates the challenge of drawing meaningful parallels. It is essential to recognize the micro discrepancies in system descriptions and boundary selections across studies, which may hinder accurate comparisons and warrant greater emphasis on establishing a common framework for evaluating UAM systems.

The majority of the existing literature has predominantly centered on the flight operation stage, or the Well-to-Wheel stage, in their CO_2 LCA studies. Evaluating CO_2 emissions during this phase is complex due to varying drone configurations and energy consumption models, which have produced conflicting results.

The CO_2 emissions resulting from the flight operation phase are decided by the energy consumption of drones. Key factors that influence energy consumption and emissions include drone configurations, such as airframe weight, battery weight, and battery capacity, as well as drone dynamics settings, like airspeed, payload weight, and other flight assumptions (Demir, Bektaş, & Laporte, 2014). Recognizing these factors is crucial in understanding the nuances of drone energy efficiency and environmental impact.

Figliozzi (2017) found that quadcopter drones loaded with light payloads are more CO_2 efficient than conventional diesel vans on a per-distance basis, when only considering the flight operation stage. Figliozzi (2020) pointed out that in the reality, the potential external factors such as temperature and headwinds will influence the energy consumption thus the CO_2 impact of drone flight, which are not reflected by the simplified drone flight pattern used in the model proposed by the study. Same with Figliozzi's study, Stolaroff et al. (2018) built a fundamental conceptual physics model for the CO_2 emissions out of drone's flight operation stage. The study compares the energy consumption and CO_2 impacts of drones with those of other transportation modes at a per-unit distance traveled level. The findings of the Stolaroff's study suggest that drones consume far less energy compared to diesel trucks. The sensitivity analysis revealed that the loaded battery weight and the regional carbon intensity of power generation played a significant role in determining the CO_2 impact intensity of drone flights (Stolaroff, et al., 2018). Thiago A. Rodrigues (2022) tested quadcopter flights to develop an empirical-data-based energy consumption model and found that drones can consume as little as 0.08 MJ/km and emit 70 g CO_2 per package, making them up to 94% more efficient than conventional transportation modes, with only electric cargo bicycles providing lower CO_2 emissions per package (Rodrigues, et al., 2022).

It becomes even more difficult to determine whether drones are more sustainable than traditional mobility options, when an LCA study expands its scope beyond just the flight operation stage but includes the aircraft production and disposal stages. In Figliozzi's study published in 2017, compared to traditional diesel ground vehicles, UASs are even less efficient in terms of production and disposal emissions per delivery (Figliozzi, 2017).

When considering the overall CO_2 impact at a network level, the status quo of drone's sustainability advantage will also be challenged. The design of drone logistics network in adopted scenarios for small UASs, plays a crucial role in determining their CO_2 impact. Adoption scenarios may vary significantly across regions and industries, with differing assumptions and settings for drone flight operations.

Stolaroff (2018) analyzed the CO_2 impacts of drone delivery in the San Francisco Bay Areas and found that even though drones are more efficient when delivering small packages, their logistics system is less efficient compared to ground trucks due to the need for more support waystations, which contribute significantly to life-cycle emissions (Stolaroff, et al., 2018).

Figliozzi (2017) extended the study to the network level of drone delivery services and also found that air drones are more CO_2 efficient for small payloads and single deliveries in rural areas, but less efficient for large payloads or when many customers are grouped in dense urban areas. His study published in 2020 further analyzed the CO_2 emissions of autonomous drones, in comparison to electric and conventional vehicles, revealing that drones become most efficient for short delivery durations with few customers grouped in the route of a ground vehicle (Figliozzi, 2020). Park et al. (2018) focused on drone flight operations for pizza delivery in South Korea and concluded that CO_2 emissions per kilometer delivery by drone were one-sixth that of motorcycle delivery, and when expanding the study to the network level, drones were more efficient in rural areas (Park, Kim, & Suh, 2018). Goodchild and Toy (2018) applied drone also in delivery service industries, investigated different delivery settings, such as delivery densities, and found that drones tend to emit fewer CO_2 emissions than trucks in service zones closer to the depot or with smaller delivery densities, resulting in a lower per delivery unit emission (Goodchild, 2018). Kirschstein (2020) proposed detailed conceptual energy consumption model and introduced transportation congestion and wind conditions as external influential factors. The results indicate that a stationary drone-based delivery system consumes more energy than a truck-based system, especially in urban areas with high customer density, while a drone-based system is comparable to electric trucks in rural settings with moderate environmental conditions (Kirschstein, 2020).

Also, there are studies on the novel truck-based drone delivery system. Baldisseri (2022) conducted a conducted an LCA study on the sustainability of electric trucks equipped with drones for last-mile delivery and found that this alternative results in significant reductions in CO_2 emissions (Baldisseri, Siragusa, Seghezzi, Mangiaracina, & Tumino, 2022).

2.1.5 Life Cycle Assessment and Electrical Vertical Taking-off and Landing Vehicle

The CO_2 impact assessment results of eVTOL LCA studies also vary due to differences in study scope and assumptions, resulting in conflicting conclusions (Zhang, 2021). LCA is data-intensive, and even small variations in data sources can lead to significant differences in study outcomes, making comparisons between studies difficult (Finnveden, et al., 2009). However, most research still come to the similar conclusion that the sustainability advantage of UAM concepts can only be achieved in certain circumstances.

In the earliest sustainability study on eVTOLs issued by André in 2019, he concluded that with optimistic assumptions, eVTOLs may compete environmentally with battery-powered cars. Even under certain ideal condition, where maximum seat utilization, clean power grid, low hovering time, and reduced travel distance are realized, only the lightweight eVTOLs can be more sustainable than traditional fossil-fueled ground-based transportation (André & Hajek, 2019). Mudumba and Chao compared CO_2 emissions from eVTOL trips and electric automobile trips in the Chicago and Dallas metropolitan areas and tested how electricity generation from power grids contributes to the emissions (Mudumba, 2021).

Kasliwal et al. suggested that within certain timeframes, eVTOLs may have a niche role in promoting sustainable mobility. The authors developed an energy consumption model to evaluate the economic and environmental impacts on the flight operation stage of a 3-seat eVTOL, compared to conventional vehicles. The results showed that, for a base case of a 100 km trip with one pilot, the eVTOL has lower CO_2 emissions per passenger-kilometer than internal combustion engine vehicles, but higher emissions than battery electric vehicles. However, when fully loaded with three passengers, VTOLs have lower emissions per passenger-kilometer than both internal combustion engine and battery electric vehicles. In a word, eVTOLs may be able to compete with internal combustion engine vehicles and potentially even battery electric vehicles in terms of CO_2 impact in a constrained scenario, which is determined by factors such as trip distance, battery capacity, seat utilization, area of operation, and grid carbon intensity (Kasliwal, et al., 2019).

Some articles directly denied the advantages of eVTOL in sustainable transportation since existing battery technology and electricity system are not clean enough to make UAM more sustainable than other passenger transportation modes. Meloa and Cerdas proposed a life cycle engineering (LCE) approach derived from LCA to estimate the potential environmental impacts generated from the production and operation of eVTOLs and suggested that the present battery technologies (specifically, lithium-sulfur batteries) used in eVTOLs are not capable of meeting the 2020 EU regulation target of 95 g CO_2eq/km for emissions (Melo, et al., 2020). In a study conducted in the Tampa Bay Area in 2022, Zhao et al. concluded that the sustainability of on-demand eVTOLs depends on the cleanliness of regional electricity production. They found that eVTOLs produce more CO_2 pollution than ground transportation modes and the possibility of increasing the number of vertiports or reducing UAM service prices could further increase CO_2 emissions (Zhao, Post, Wu, Du, & Zhang, 2022). Liu et al. has similar findings in China's context. They found that the emissions from eVTOLs were even higher than those from on-road internal combustion engine vehicles and battery electric vehicles. By looking forward to the development of battery technologies and a cleaner power grid, eVTOLs might win its sustainability competency in the future (Liu, et al., 2022).

2.2 Environmental Impact Measurement of Urban Air Mobility Infrastructure

Coen Van der Giesen, et al. recommend conducting Ex-Ante LCAs (as opposed to an Ex-post, also called retrospective LCA), which involve scaling up emerging technologies using scenarios of future performance and comparing them to the evolved incumbent technology, at full operational scale (van der Giesen, Cucurachi, Guinée, Kramer, & Tukker, 2020). That is also why most LCA studies of UAM are conducted in the scaled-up system level and why logistics network mapping and route optimization are highlighted repeatedly for measuring the overall CO_2 impacts of the whole UAM network.

In the realm of system-level analysis for UAM, the concept of a vertiport holds undeniable significance. Social attention, capital investment, and academic research surrounding UAM and vertiports grows explosively (Schweiger & Preis, 2022) since Uber

Elevate released the whitepaper "Fast-Forwarding to a Future of On-Demand Urban Air Transportation" in 2016 (Uber Elevate, 2016). According to the report issued by EASA in 2021, infrastructure is the biggest challenge of the early adoptions of UAM (EASA, 2021). The integration of UAM vehicles into the existing urban transportation system requires the development of ground infrastructure to support the safe and efficient UAM operation. Normally, the ground infrastructure is referred to as "vertiport."

2.2.1 The Concept of Vertiport

Vertiport is not initially used as an UAM concept. The concept of "vertiport" was firstly drawn from in the publication of Advisory Circular 150/5390-3 issued by U.S. Federal Aviation Administration (FAA) for the application of civil tiltrotors in 1991. FAA defined vertiport as:

An identifiable ground or elevated area, including any buildings or facilities thereon, used for the takeoff and landing of tiltrotor aircraft and rotorcraft (FAA, 1991).

The newest official definition of "vertiport" issued by FAA in its Engineering Brief #105 is:

An area of land or a structure, used or intended to be used, for electric, hydrogen, and hybrid VTOL landings and takeoffs and includes associated buildings and facilities (FAA, 2022).

The first accepted definition of "vertiport" in European areas was issued by EASA in 2019 and then adopted widely in other official regulatory documents. EASA defines "vertiport" as:

An area of land, water, or structure used or intended to be used for the landing and take-off of VTOL aircraft (EASA, 2019).

The terms used to depict the UAM ground infrastructures vary from one to other. The supportive infrastructure could be constructed on the ground, over water, or elevated on the rooftops of the existing buildings. Terms including droneport, aerodrome, vertihub, vertistop, vertiplace, vertipad, skypart, and pocket airport, etc. are used according to the archetype design, operation features, and the network planning of the infrastructure ecosystem. For example, vertistop refers to the minimal infrastructure with a single touchdown and lift-off area (TLOF) pad (FAA, 2022). A complex infrastructure system could include the landing pads, charging ports, hangars, communication center, maintenance facilities, and other necessary facilities to not only fit into the regulation requirements, but also provide the convenience to the densely populated areas. Vertiport is the most prominent term adopted by the scholars and industrial practitioners (Schweiger & Preis, 2022). Therefore, in this report, regardless of the utilization objectives or what types of vehicles the ground system served for, all the infrastructure is referred to as "vertiport."

2.2.2 System Analysis of Vertiport

Figure 5 summarizes the existing studies focusing on the ground infrastructure system of UAM. The scattered state of research on vertiports can be attributed to the absence of established operations within the field. Most vertiport services are still in the conceptual stage and the design modules are still on paper. Start-up companies like Skyports and Lilium are testing their vertiport operations in 2022. Urban-Air Port unveiled their first fully operated vertiport in UK (Coventry City Council, 2022).

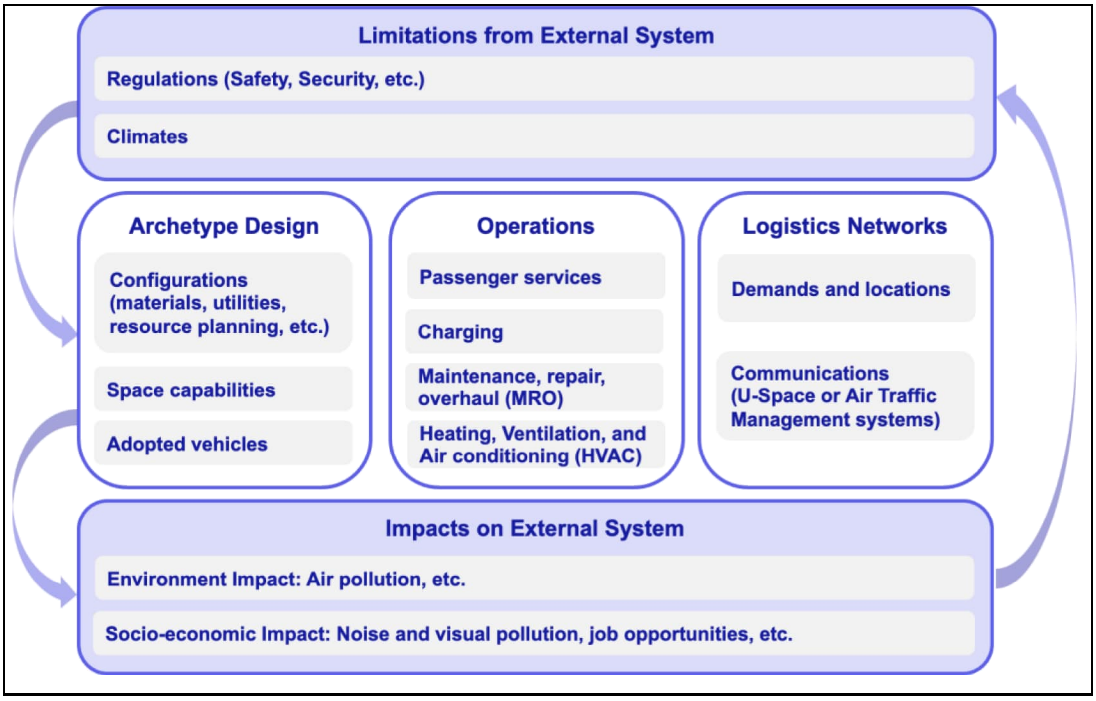


Figure 5. System of system analysis of vertiport.

Maier's idea of viewing the ground infrastructure as a system-of-systems (SoS) could be utilized to analyze the vertiport (Maier, 1998), so maintaining the SoS requires a holistic approach that considers the interconnections between the components inside.

Limitations from External System. In the UAM vertiport SoS, the vertiport can be influenced by external systems such as regulatory and legislative frameworks and uncontrollable natural factors like meteorological conditions.

EASA published the world's first detailed prototype technical specifications for the design of vertiports in March 2022. To satisfy the minimum technical requirements, the vertiport has to offer at least one final approach and take-off area (FATO), at least one touchdown and lift-off area (TLOF), and an extra safety zone that extends beyond the FATO serves as a protective measure (EASA, 2022). The taxiways and stands for parking, and other charging or communicating utilities are optional according to the real requirements.

The uncontrollable external factors in the UAM ecosystem usually refer to weather conditions. The UAM flight operations of VTOLs should at least meet the critical point of Certified Minimum Performance (CMP) requirements (EASA, 2020). Specifically, EASA provided the requirements regarding the performance and controllability of wind conditions and visibility during falling and blowing snow in its publication of proposed means of compliance (EASA, 2021).

Though historic weather characteristics play a crucial role for the location selection, design, capability, and other operating concepts of vertiports, there is limited literature examining the metrological impacts on UAM infrastructure operations, as most vertiport operations are still at the conceptual stage. Studies on weather variations and their impacts are usually conducted in conjunction with geographic influence analysis. These studies on weather impacts on UAM operations are typically conducted on a regional level and are subject to regional limitations.

Steiner (2020) states that the UAM planners and operators must take the weather-related factors into consideration when making decisions about the applicable infrastructure operating hours (Steiner, 2020). Berchoff (2020) identifies that winds, temperature, ceiling, and visibility could be the most impactful urban weather challenges (Berchoff, 2020).

The circadian and seasonal cycles of weather patterns present a dynamic and challenging operating environment UAM operations (Berchoff, 2020). Compared with traditional airplanes and helicopters, electrical UASs are typically smaller and lighter so that they are more sensitive to weather conditions, requiring a greater degree of precision and control during takeoff, level flight, and landing. Reiche et al. (2018) analyzed meteorological impacts on UAM operations in several U.S. cities and found that on average, 6.1 hours per day in winter, 7.3 hours per day in spring, 2.9 hours per day in summer, and 2.2 hours per day in fall could be potentially affected by significant weather conditions, assuming a daily operational window of 7 a.m. to 6 p.m. (Reiche, Brody, McGillen, Siegel, & Cohen, 2018). The study used METAR surface data and pilot reports to weigh the “impact scores” of various weather factors such as temperature, precipitation, ceiling, visibility, wind, etc. A significant limitation of the present study is the potential discrepancy between the weather data obtained from METAR reports and the actual climatic conditions within urban areas. Since METAR data specifically reflects the weather conditions at a particular airport and its vicinity, with a particular emphasis on approach, landing, and departure directions, it may not always accurately represent the broader urban climate. This discrepancy highlights the need for a more comprehensive approach to gathering weather data, ensuring a more accurate representation of the Very Low-Level airspace (VLL airspace) in urban environments.

The impacts of urban micro-climate systems are also highlighted as the potential challenges of vertiport operation. Micro-climate factors like wind channeling and turbulence caused by buildings in urban areas would place significant influence on the performance and safety of UAS in urban settings (Steiner, 2019). Given the unique and complex conditions, traditional empirical weather data provided by aeronautical meteorological service providers today might not be sufficient for studying the impacts of micro-climate systems on UAM operations anymore (Steiner, 2020).

To address the weather data collection challenges mentioned above, modern technologies such as weather sensors and information systems are being developed. The adoption and implementation of these technologies in UAM operations could have some impact on the sustainability evaluation of the system. However, how could we quantify the effects of something before it occurs? It is nearly impossible to measure the potential impact with certainty since the lack of empirical evidence and data. Therefore, the CO_2 emission that may arise from the use of these technologies have not been included in this LCA study.

Vertiport System. Three high-level categories, archetype design, type of vertiport operations, and logistics networks collectively determine the inherent form and function of the UAM vertiport system. A plethora of elements, including the configuration design, construction material selection, resource allocation strategies, space capacities, land utilization designations, and the types of UASs to be served, will significantly impact the ultimate archetype design of the vertiport (Schweiger & Preis, 2022). Additionally, when operating the vertiport, the determinant factors could be the provision of passenger services, the alignment of use cases with the vertiport capabilities, the availability of charging services, the necessity of incorporating maintenance, repair, and overhaul (MRO) and heating, ventilation, and air conditioning (HVAC) systems, and the extent to which those services are required to be offered.

Developing a holistic vertiport network capable of effectively serving high-density urban areas requires careful selection of vertiport locations and establishment a reliable UAM communication network through sophisticated air traffic management (ATM) or U-space systems. Selection of vertiport locations necessitates considering socio-demographic factors, local commuting patterns, and city planning characteristics in the system model design. Also, establishing UAM communication networks and integrating them with existing urban infrastructure and transportation networks is vital for seamless connectivity and user experience.

In a word, to achieve the highest level of maturity in UAM operations, collaboration with local authorities, stakeholders, and communities is essential to address concerns and ensure the successful implementation of vertiports in urban settings.

Socio-economic and Environmental Impacts on External System. Vertiports can exert socio-economic impacts on external systems. For instance, the sociological influence encompasses noise and visual pollution, which may affect local communities by changing their daily routines and hinder public acceptance. However, the potentially positive economic consequences, which include the emergence of new business and job opportunities in various sectors such as infrastructure development, UAM vehicle manufacturing, and support services, may foster the public acceptance. Additionally, vertiports can also trigger disruptive alterations throughout the traditional transportation industry’s value chains, leading to shifts in investments, technological innovation, and the potential restructuring of existing business models.

Environmental impacts involve resource consumption during the construction of new vertiports, including land use changes, raw material extraction, and energy consumption. Construction activities and vertiport operations can contribute to GHG emissions so that climate change induced by air pollution resulting from the establishment and operation of vertiport systems is another critical concern. Sustainable construction practices, efficient design, and the use of eco-friendly materials should be carefully considered to minimize resource utilization and reduce the environmental footprint.

These impacts, in turn, affect the regulation and local climate, creating a dynamic interaction between the vertiport and its external environment. For instance, the socio-economic impacts like the changes in citizens’ sociological behaviors might in turn trigger the public concerns about the safety and security issues and then prompt regulatory necessities. Whereas environmental impacts, such as changes in air pollution levels, may either accelerate or decelerate the progression of climate change, leading to subtle alterations in weather patterns. Reciprocally, the UAM deployment would be influenced by subtle climate alterations, even though the changes require long-term observations.

The precise magnitude and distribution of socio-economic and environmental impacts hinge on factors such as technological readiness, community acceptance of UAM, service demand, types and frequencies of UAM services offered, vertiport network configuration, and user behavior. Therefore, Therefore, to optimize the vertiport network, careful planning and analysis are necessary to maximize economic and environmental benefits while minimizing sunk costs and negative externalities.

2.2.3 The Vertiport Network and Carbon Dioxide Life Cycle Assessment

The optimization of the UAM infrastructure network and logistic system has garnered considerable attention in recent scholarly discourse. The elements, capabilities, size, and network design of vertiports can vary depending on different time horizons, maturity levels of UASs, and the adoption scenarios (Schweiger & Preis, 2022). It is commonly agreed the environmental impacts including CO_2 emissions are heavily dominated by the infrastructures implementations for providing the readiness of flight and the ground services, but scholars admitted that the large uncertainties such as local climate, fuels, the manner of operations make the estimation challenging. Under such a status quo, scholars prefer to estimate the CO_2 impacts by seeing the holistic vertiport network as a system rather than to check the CO_2 emission generated by a single vertiport. They estimate and minimize the environmental impact of UAM infrastructure in network level since a single UAM infrastructure is a complex system that is vulnerable to emergent operation behaviors and unpredictable results (Patel, Gunady, Rao, Wright, & DeLaurentis, 2022).

The infrastructure system mapping directly decides the number and location of vertiport constructed, and even the frequency of the UAS battery replacement and depreciation. Those are direct CO_2 emission sources. If the infrastructure implementation is included in the scope of a lifecycle assessment of UAM, it is unavoidable to map the whole vertiport network as a system and simulate the possible flight demand in certain adopted scenarios.

In existing literature, scholars utilized the on-demand model such as agent-based model that predicts the UAM demand based on the socio-demographic data to simulate the vertiport network and related flight routes. The adoption scenarios are normally limited to flying taxi and public transportation (passenger eVTOL), or package delivery (package drones).

Rothfeld's model set the target as minimizing the UAM operational cost (Rothfeld, Balac, Vetrella, & Schmid, 2019). Rothfeld et al. conducted the system-wide transport analysis to quantify the performance of UAM in Munich, Germany, based on the Dynamic Vehicle Routing Problem (DVRP) Multi-Agent Transport Simulation (MATSim) model contributed by Maciejewski (Maciejewski, 2016). The framework simulates and optimizes the UAM routes by modeling the chains of trips of individual households according to their daily activity patterns (Rothfeld, Balac, Vetrella, & Schmid, 2019). The study provides suggestions on the selection on the vertiport location and the optimized usage of airspace. In Rothfeld's model, the UAM typically mirrors the unmanned ground-based taxis or private cars since the limitation of the flight distance of eVTOLs so that they can only serve for intra-city operations. Ploetner et al. extends the on-demand transportation model by introducing the multiple indicators including environmental, transport-business related, and socio-economic factors and concludes that UAM will not significantly change the daily mobility situation in Munich (Ploetner, et al., 2020). In this simulation, eVTOLs serves as a complement to public transportation.

UAS last-mile transportation models are intensively studied in urban contexts, no matter if they are small UAS or midsize eVTOL. In the fundamental study on the CO_2 emission of drones, Stolaroff et al. adopted the small UAS in the last-mile commercial package delivery scenarios. He stressed that the CO_2 emission from the warehouse operations will greatly increase the life cycle impacts of drones (Stolaroff, et al., 2018). The model roughly estimated the warehouse potential CO_2 emissions based on the UPS metrics issued in 2015 (UPS, 2016). A hypothetical coverage map for the greater San Francisco Bay Area is modeled to estimate the minimum number of nodes needed for drone delivery.

The study highlighted that, compared to the conventional truck pathways, a drone delivery system might require higher warehouse energy consumption in some cases. Notably, the study did not compare the energy requirements for operating individual warehouses across different transportation modes. Instead, the authors examined the total energy consumption associated with operating warehouses in the transportation network of San Francisco Bay Area. The authors assumed that the energy consumption levels of individual warehouses were the same for drones and trucks, but they noted that due to drones' shorter flight range, more warehouses or depots may need to be built and operated to make UAM services available and cover the entire Bay Area (Stolaroff, et al., 2018). In a word, the higher-volume CO_2 emissions are not determined by whether the infrastructure is used for drones or delivery trucks, but rather due to the limited flight endurance of battery-operated drones. Drones can only serve for short-distance delivery, so UAM requires the establishment of extra infrastructure nodes compared to trucks (Stolaroff, et al., 2018).

Patel et al. treated UAM infrastructure as a system-of-systems (SoS) and utilizes SoS modeling to optimize power allocation and fleet dispatch for demand response, thereby calculating the system's performance in terms of UAM carbon emissions (Patel, Gunady, Rao, Wright, & DeLaurentis, 2022). Prakasha et al. used a similar SoS agent-based simulation to evaluate the impact of different eVTOLs, considering various factors such as fleet combinations, technology scenarios, and operational strategies. The simulation-driven framework provides a comprehensive understanding of the SoS design space that can guide the future deployment or optimization of UAM network for a given city (Prakasha, Naeem, Ratei, & Nagel, 2022).

ElSayed and Mohamed provides a framework for designing the UAS system that will achieve the environmental benefits of GHG emissions reduction and stressed that a smarter airspace network planning, in other words, airspace discretization, could reduce the energy consumption of the UAS operations (ElSayed & Mohamed, 2022). Additionaly, ElSayed et al. also proposed an innovative vertiport design to collect the solar energy and thus minimize the environmental impacts of the UAM system by deploying the building-integrated photovoltaics (BIPV) roofs. The new materials application, the minimum-energy trajectory algorithm, and the multi-objective optimization models are applied in this simulation, in order to meet the demands of customers by assigning a minimum number of solar recharging stations to increase the coverage range of UASs while minimizing the cost of energy usage and decarbonization target (ElSayed, Foda, & Mohamed, 2022).

2.3 Emergency Medical Services

2.3.1 Urban Air Mobility in the Context of Emergency Medical Services

Prehospital emergency medical services (EMS) are a vital part of modern society. In western societies, the majority of EMS patients are aging people with chronic ailments, experiencing acute complications related to their long-term health conditions, and possible needs of out-of-hospital health and social care (Ilkka, 2022).

The history of EMS can be tracked with the war history together. The first hospital-based ambulance services in the US started in 1865 (National Highway Traffic Safety Administration, 1996). The first petrol-driven ambulance appearing on London's streets in 1904 (Pollock, 2013). During World Wars I and II, EMS made significant advances in military settings, but the civilian setting lagged behind until the 1960s, when the importance of transport in patient outcomes was finally recognized. EMS are intensively developed for the improved survival rates for out-of-hospital cardiac arrest in European regions in the 1990s, and the undergoing significant development of the logistics system since the 2000s.

Air Emergency Medical Service (Air EMS) is a critical segment in EMS that provides timely medical transport capability. Helicopter emergency medical services (HEMS), as one of the most important mobility of Air EMS segment, have demonstrated immense value when functioning in remote areas, such as mountainous or densely forested regions, or traversing distances exceeding 100 kilometers.

However, HEMS has been a topic of debate due to its low cost-effectiveness, limited availability during inclement weather conditions, in combination with a high noise profile (Ilkka, 2022). The low cost-effectiveness stems from the inherently high operating expenses of helicopters, which include fuel costs, maintenance, and crew training. Limited availability during inclement weather conditions is another concern. Helicopters face operational challenges in poor visibility, heavy rain, or strong winds, which can result in increased response times or grounded flights. Furthermore, in urban settings, a high noise profile is another issue associated with HEMS. Helicopters generate significant noise during operation, which can cause disturbance to urban residents, so that helicopters may not always be the most practical option for emergency services in densely populated areas and further lead to restrictions on their use. Consequently, given the low utilization rates and potential safety concerns regarding the accident rate of HEMS, maintaining constant HEMS availability may not always be required. This situation in turn leads to increased costs for a type of service that may not be fully utilized, further questioning the cost-effectiveness of HEMS in urban settings.

Recently, the maturation of UAM systems presents an opportunity to tackle noise, cost, and safety challenges associated with HEMS (Chappelle, Li, Vascik, & Hansman, 2018). First of all, electric aircraft such as eVTOLs provide opportunities to reduce noise contribute due to their inherently quieter propulsion systems compared to conventional fossil-driven helicopters. The electric motors in these aircraft produce less noise and vibrations during operation, resulting in a quieter flight experience.

Furthermore, though near-term UAM systems may face weather limitations similar to HEMS, employing UAM is expected to enhance safety and reduce costs. Utilizing electric aircraft, such as eVTOLs, can decrease operating costs per seat mile by 26% compared to fossil-driven helicopters, thanks to simplified flight controls, advanced sensors, and autonomous technologies (Duffy, Wakayama, Hupp, Lacy, & Stauffer, 2017). Additionally, during emergencies, in addition to eVTOL, light and manurable package drones could serve as a supplementary tool for delivering medicine or medical tools or packages during emergencies, which are faster than ambulances and much cheaper than HEMS, further cutting the Air EMS costs.

2.3.2 Life Cycle Assessment on Urban Air Mobility in the Context of Emergency Medical Services

The body of academic literature regarding the application of UAM in EMS scenarios is relatively scarce, while the industrial operators like UPS announced that drone healthcare logistics is a priority segment, also Cohen (2019) and Drones in Healthcare (2020) have reported the adoption of UAM for medical deliveries over short ranges (Cohen, 2019). The limited UAM academic research in healthcare industries also focuses on how to optimize the flight route design to improve UAM efficiency for delivering the medical services. The study conducted by Al-Rabiaah focused on building up the models for the location selection issues of UAS: a sophisticated-chosen launching centers of drones could solve the pain point of UASs, the range constraint, thus, to maximize patient service coverage (Al-Rabiaah, Hosny, & AlMuhaideb, 2022). Ghelichi et al. researched how to optimize UAM in healthcare by developing an optimization model for a drone fleet delivering medical items to hard-to-reach areas in Louisville, KY. They proposed a solution for task assignment, trip scheduling, and charging station selection to minimize the service time (Ghelichi, Gentili, & Mirchandani, 2021).

There are scarce comprehensive studies that evaluate the environmental impacts of UAM in the healthcare industry. There is currently no case study available that specifically examines the environmental effects of implementing UAM as a supplementary mode of transport in the healthcare sector. This represents a significant gap in the current body of research, as UAM could have profound impacts on healthcare delivery services, particularly in emergency circumstances.

The use of package drones and passenger eVTOL in healthcare delivery services has the potential to revolutionize emergency scenarios by enabling the delivery of critical medical supplies and equipment, or the provision out-of-hospital services to remote or hard-to-reach areas (Mohamed, Al-Jaroodi, Jawhar, Idries, & Mohammed, 2020). The adoption of drone technology could facilitate the delivery of surgery instruments, blood for transfusions, automated external defibrillators (AEDs), diagnostic samples, essential medicines, and even scarce organs in urgent situations, or the moving of patients or medical specialists to the desired destinations (Krivohlavek, 2021).

Adopting UAM in EMS would significantly reduce the time and costs associated with traditional transportation methods, such as ground-based ambulances. The time saving is direct and more obvious since drones can circumvent transportation congestion and fly directly to their destination, resulting in significant time savings. Besides, healthcare organizations can ensure that critical services are accessible to patients who locate in remote locations and cannot be reached by ground modes of transportation due to the time factor, enhancing the overall efficiency of emergency medical response and distributing the medical resources across a wider geographical area. The cost savings can be realized in several ways and might not be directly linked to the transportation cost but more indirect. The indirect but valuable cost savings can result from the reduction of the waiting time and the possibly reduced hospitalization periods. In such cases, a huge amount of hospitalization fees could be saved due to the fast delivery of surgery instruments or samples.

In EMS scenarios, the priority is always the time whilst not compromising safety. The rapid response and delivery of life-saving equipment and personnel by UAM can greatly increase the chances of saving lives and reducing the burden on medical services. Therefore, embracing UAM technologies seems to be a highly desirable direction for the market, offering numerous potential benefits and improvements over traditional approaches. Given the critical role played by healthcare systems, it is important to gain a comprehensive understanding of the environmental impact of UAM adoption in this industry to ensure that the benefits outweigh the potential drawbacks.

While some studies suggest that the mission-based drone delivery logistics system may be less cost-effective and less environmental-friendly than the well-developed ground transportation logistics system due to the limited delivery capacity, shorter flight ranges, and unmature technologies of UAM. Unlike ground transportation and helicopter systems, which have been developed over decades with well-established infrastructure and traffic management systems, UAM is still an emerging technology that lacks similar support. Moreover, the power systems for UAM (batteries, hydrogens, and alternatives) are also waiting to be improved.

Measuring the end-to-end CO_2 footprint and identifying what point could be improved in the future is more important to reaching the conclusion that whether UAM, at this moment, is more or less sustainable than other mobilities. Just as Holden et al. wrote:

UAM may be considered sustainable if it satisfies a basic transport need without compromising long-term ecological sustainability (Holden, Linnerud, & Banister, 2013).

Future research should focus on assessing the environmental impact of drone adoption in emergency medical scenarios to inform the development of sustainable and effective healthcare delivery practices.

3 Cradle-to-Grave Life Cycle Assessment Models and Practical Applications

Life Cycle Assessment (LCA) can be classified into Ex-Post and Ex-Ante LCA. Traditional LCA methods are more suited to Ex-Post assessments, which rely on empirical data from mature products in use commercially for extended periods. However, Ex-ante LCA is performed when new technologies are still in their development phase, requiring time to reach the maturity of the technology, market introduction, and ubiquitous operations. In the stage prior to a product or technology being widely implemented commercially, comprehensive data and insights about the subject may still be scarce or unavailable.

NASA has issued the document to specify the definitions of UAM Maturity Levels (UML), from UML-1 to UML-6, based on the density of aircraft volumes, the complexity of operating conditions such as weather conditions, and the automation of UAM aircrafts (Koumoutsidi, Pagoni, & Polydoropoulou, 2022). UML-1 represents aircraft projects nearing technical certification completion, involving agreement on operation plans and testing. Additionally, practitioners started addressing community integration through prototype demonstrations, assessing noise, local facilities, and airspace operations in potential markets. UML-2 includes initial flight operations with low volume, primarily in early adopter areas and community integration should pose some challenges or uncertainties in urban settings (Goodrich & Theodore, 2021). Even though in the academic world, there are lots of state-of-art simulations for managing UAM towards UML-4 or UML-5, evidence shows that the current maturity level of UAM is between UML-1 and UML-2 and all the potential use cases of UAM could exceed UML-2 by 2040 (Koumoutsidi, Pagoni, & Polydoropoulou, 2022).

From the perspective of Technology Readiness Level (TRL) scale, which is a general industrial standard, a maturity level between UML-1 and UML-2 might correspond to a TRL of UAM vehicles that is beyond 5. It means that the technology of UAM vehicles is almost ready for large scale operation but does not imply that the necessary components or subsystems to secure the operation of the whole UAM system are all reaching to such a maturity level. Supportive infrastructure and systems, such as vertiport networks and communication technologies required for UAM operations, may still fall between TRL1-5, presenting a delay in overall readiness. Figure 6 shows the Relation between TRL and LCA, applied to both the core and supportive technologies within the UAM system.

Following the standards issued by ISO14040/14044: 2006, this study evaluates the strong cause-effect quantitative Cradle-to-Grave CO_2 life cycle impact for a nominated package drone, which is Falcon L, and a passenger eVTOL aircraft, which is EH216, along with a regression-based quantitative evaluation of the life cycle impact of infrastructure systems (vertiports). The study assesses CO_2 emissions measured in carbon equivalents. This chapter explains the application of the LCA framework and methodologies in the study and outlines the fundamental objectives and modeling choices.

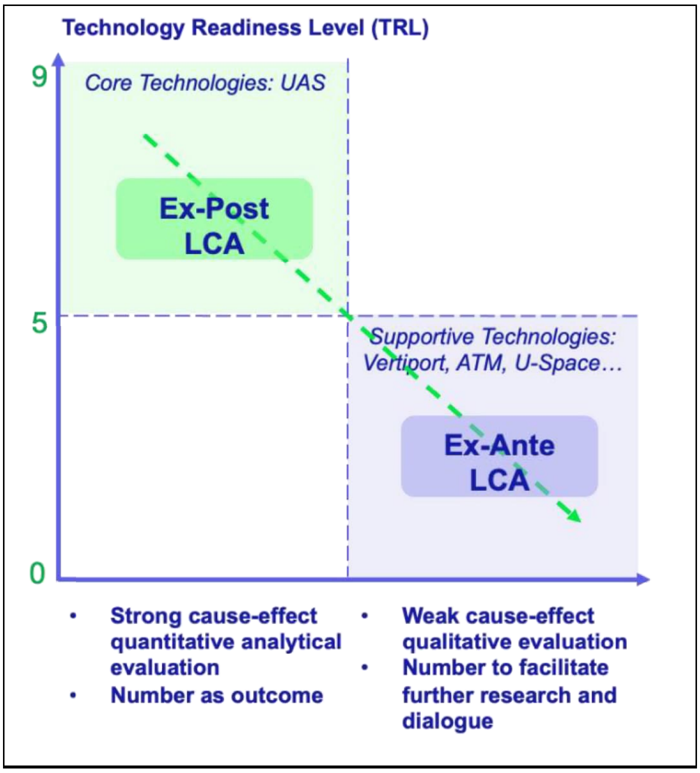


Figure 6. System of system analysis of vertipor relation between TRL, LCA, and UAM technologies (van der Giesen, Cucurachi, Guinée, Kramer, & Tukker, 2020).

3.1 Goal and Scope Definition

This chapter covers the first phase of Life Cycle Assessment (LCA) is the goal and scope definition (ISO, 2020).

Product and System in Scope. The LCA study is under the midpoint impact assessment categories that represent a specific aspect of environmental impact. Global warming potential, specifically CO_2, is measured in this study. The LCA study quantitatively evaluate the CO_2 emissions generated from the UAM systems, focusing on the adoption of drone (Falcon L) particularly employed for urgent medical package distribution and 2-seat medium size eVTOL vehicle (EH216) particularly employed for the expedited transportation of personnel (medical professionals or patients).

In the subsequent paragraphs, a complete aircraft configuration encompasses both the airframe and its power system, which, in our case, refers to Lithium-Polymer batteries. Furthermore, the study conducts a regression-based quantitative evaluation of the CO_2 emissions generated by infrastructure systems, specifically vertiports, which have significant environmental impacts on UAM systems. Overall, the study examines which factors will influence the lifecycle CO_2 emissions of UAM systems in terms of climate impact, or in other words, the degree of sustainability.

System Boundary Definition. The study deploys a quantitative analysis on the UAM vehicles. For the quantitative Cradle-to-Grave CO_2 LCA study on UAM vehicles, the system excludes the insignificant flows which refers to the insignificant life-cycle inventories of UAM system. For examples, the emission flows from aircraft engineering, administrative, or marketing activities, data corresponding to which are hard to be captured with current UAM maturity level and their impacts can be ignored without affecting the LCA study's conclusions.

The arguable part of the system boundaries is whether background systems, specifically the construction, maintenance, and operation of vertiports in our case, should be included into the LCA study. There are arguments that only when UASs have become a viable substitute for other mobilities (ambulances, electrical vans, or helicopters in the EMS scenarios) can UAM and other transportation modes (including both the vehicles and background systems) be comparable at the system level. To be more specific, when the sufficient operations of UASs could potentially substitute a significant portion of emergency ambulance trips, the construction, maintenance, and operation of ground road systems might be reduced or suspended. Otherwise, introducing UAM as a supplementary transportation option would not significantly affect the development of the existing mobilities. So, it is better to compare the marginal impact of each transportation mode (André, 2022).

However, vertiports are identified as the most significant flows within UAM system and will generate highest amount of the CO_2 emissions. To tackle this issue, the study will assess carbon impacts of a sample vertiport and incorporate infrastructure CO_2 emissions as a manipulated variable in the sensitivity analysis. By defining low, base, and high cases for infrastructure CO_2 emissions and integrating the CO_2 emissions from each case into the LCA model, the degree to which the UAM system's emissions are influenced by infrastructure emissions could be tested.

In contrast to the robust, cause-effect quantitative LCA emission models created for UASs, the regression-based LCA models for utilizing a sample vertiport data for predicting emissions of vertiports located in different regions are serving to promote discussions and dialogues. The Combination of Ex-Post and Ex-Ante LCA approaches is intended to offer a comprehensive view of the sustainability level of the technologies or systems involved in the nowadays UAM system. More detailed system boundaries will be further discussed in Chapter 3.2.

Functional unit. For both Falcon L and EH216 the functional unit of the CO_2 emission from production and disposal stages is kg CO_2eq per aircraft. The difference between the two aircraft lies in the functional unit for CO_2 emission from operation stages, which are normalized to g CO_2eq per package-kilometer traveled for Falcon L, and similarly, they are normalized to g CO_2eq per passenger-kilometer traveled for EH216. The functional Unit for the construction and operation impacts of Infrastructure is kg CO_2eq per vertiport.

Scenario Type. The UAS flight was employed in EMS scenarios across the four cities selected by the AiRMOUR project. The four cities are Stavanger in Norway, Helsinki in Finland, Luxembourg, Kassel in Germany. The energy landscape in 2022 is set as a standard scenario. Energy landscape changes across time and it serves as a variable in the sensitivity study, wherein adjustments to the energy landscape are made to evaluate the potential consequences of varying projections and assumptions on the environmental repercussions of UAS operations within the EMS context.

3.2 Life Cycle Inventory Analysis

According to ISO14040/14044: 2006, the CO_2 life cycle of UAM, including both UAM vehicles and infrastructure, starts from raw material extraction, where natural resources are collected, materials are extracted, to produce the necessary components for UAM vehicles and vertiports. Following extraction, the raw materials are transported to processing facilities where they are transformed into usable materials for production. The production phase of UAM vehicles involves the assembly of various components, such as propulsion system, airframe, and power systems, which are battery packs in our cases. The construction phase of vertiports typically involves the creation of hangars or other related building structures. The use phase of UAM involves not only the operation and maintenance of the UAM vehicles but also the UAM infrastructures, with energy consumption and associated CO_2 emissions varying depending on the vehicle type and fuel source. In the end of life, UAM systems can be disposed directly or in a more environmentally friendly way: being re-used, re-manufactured, or recycled. Figure 7 visualized the life cycle of the UAM system.

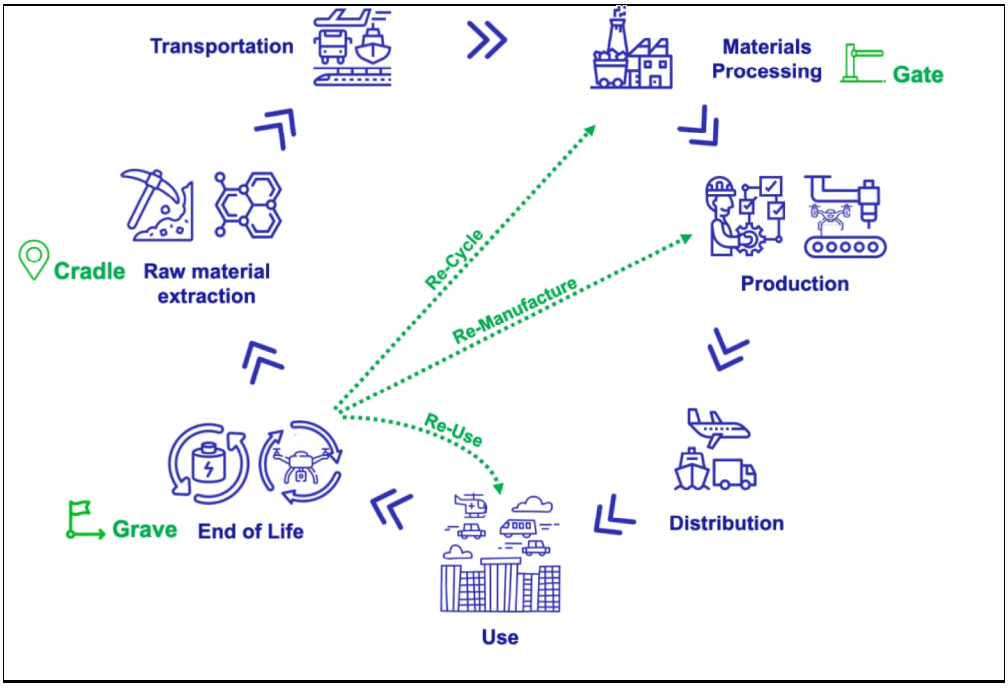


Figure 7. Cradle-to-Grave life cycle of UAS from raw material extraction to end of life (ISO, 2020).

The life cycle stages are simplified into 3 stages: Sourcing & Production, Operation, and End of Life, See Figure 8. Followed by the system boundary guidelines established in Chapter 3.1, this study omits inventories deemed insignificant and focuses solely on life cycle inventories that are presumed to have a substantial impact on the environmental assessment outcomes.

Within the Sourcing & Production stage, the assessment scope covers the necessary resources and energy for constructing the aircraft's frame, energy storage system, and power unit, which refers to Lithium-Polymer batteries in our case. CO_2 emissions are determined by the primary materials composing the main aircraft components, like battery packs and airframe, along with the associated carbon emission factors for sourcing and producing those materials. At this stage, Aircraft Design & Integration, Aircraft Engineering, Infrastructure Construction[1] are excluded to the scope of this LCA study since CO_2 emission data relevant to those life cycle inventories are inaccessible and existing research have suggested that the environmental impact of those elements is neglectable. Johanning, who conducted an LCA

[1] Infrastructure Construction is different with Infrastructure Materials. Infrastructure Materials evaluates the environmental impacts associated with extracting, processing, and manufacturing materials raw materials and components required to create the infrastructure supporting infrastructure systems, like vertiports. Infrastructure Construction covers the processes involved in assembling and constructing the infrastructure using the infrastructure materials, evaluating environmental impacts of construction activities, such as energy consumption, emissions from machinery, transportation of materials to the construction site, and waste generated during the construction process.

on Airbus A320, found that the contribution of Aircraft Design & Integration to the total environmental impact was around 0.1% (Johanning & Scholz, 2014).

Within the Operation stage, the assessment scope covers the CO_2 emissions generated from Infrastructure Operation Power Requirements and Infrastructure Operation Energy Consumption. As mentioned in the Literature Review chapter, the operational stage has the most significant impact on emissions from the UAM system, and methodologies for measuring environmental impact of Operation stage are well-developed. At this stage, aircraft and infrastructure maintenance are excluded to the scope of this LCA study because UAM is still in the conceptual operation stage with limited maturity level, and such activities have not yet occurred outside of laboratories and testing fields.

The End-of-Life stage covers the same elements as the Sourcing and Production stage: the system is retired and needs to be disposed, recycled, or reused. So, with no surprise, this stage covers the necessary resources and energy for dealing with the retirement of the aircraft's frame, energy storage system, and power unit, which refers to Lithium-Polymer batteries in our case. CO_2 emissions are determined by the disposal, reuse, or recycle of the main aircraft components, along with the associated carbon emission factors for those processes. However, normally the infrastructure ends up with reconstruction. The reuse of infrastructure pertains to the background system's secondary life extension and is excluded from the life cycle scope of the UAM study. So, only the end-of-life CO_2 impact of UAM vehicles is measured and included in this study. In addition, at the end-of-life stage, aircraft and infrastructure dismantling are excluded also since CO_2 emission data relevant to those life cycle inventories are inaccessible.

Research found that the environmental impacts stemming from the disposal of UASs may either increase or reduce the CO_2 emissions resulting from their sourcing and operation. The specific effect largely depends on the end-of-life management strategies implemented, including the reusing and recycling of the subsystems, components, and materials of UASs. Some innovative end-of-life processes could further mitigate the overall life cycle impact of UASs. Taking the battery system as a concrete example, regardless of whether extra CO_2 emissions are generated or more CO_2 are mitigated by the end-of-life processing of the battery systems, these effects will be captured by the life-cycle carbon emission factors associated with Lithium-Polymer batteries. Therefore, the study uses Monte Carlo simulation to generate a large number of random scenarios within the established boundaries, allowing for a probabilistic analysis of the end-of-life strategies. This technique helps account for uncertainties in the input parameters, providing a more robust understanding of the potential outcomes and effectiveness of different strategies in reducing environmental impact.

As shown in the bottom line of Figure 8, secondary background processes, such as transportation and distribution, administration, and marketing activities, are excluded from the LCA study due to their relatively negligible environmental impacts (Johanning & Scholz, 2014). Focusing on the negligible elements might distract the audience from the primary objective of understanding and addressing the most significant contributors to the system's environmental impact.

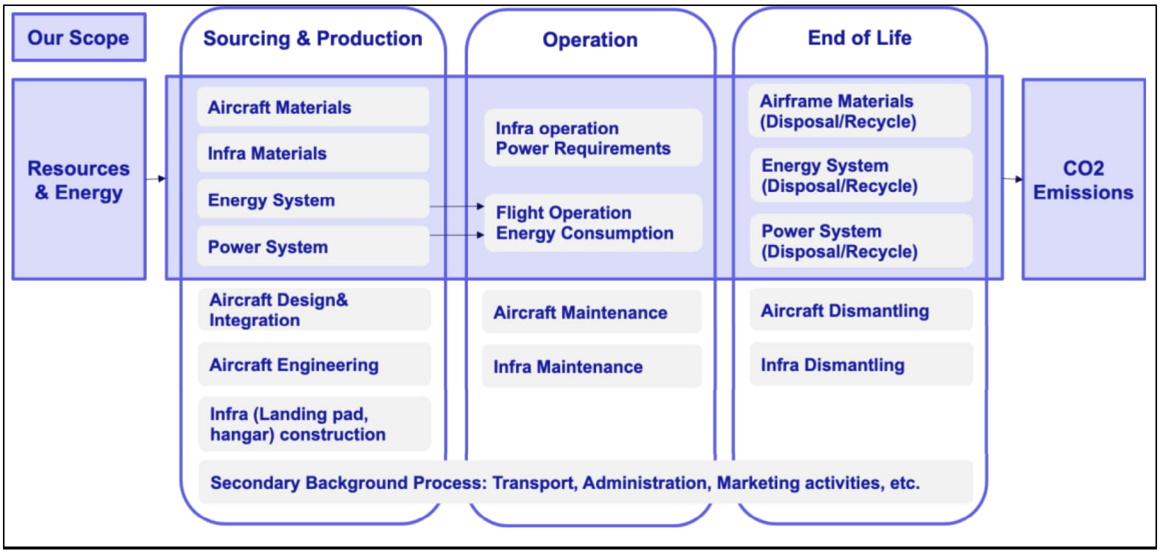


Figure 8. Life cycle stages and inventories of UAS.

3.3 Life Cycle Impact Assessment and Interpretations

Chapter 3.3 includes the life cycle impact assessment on the life cycle inventories of UASs outlined in Chapter 3.2. The assessment includes CO_2 impacts of the airframe, energy, and powertrain systems in the Cradle-to-Gate & Gate-to-Grave stages, which refer to sourcing and production stage, and end-of-life stage respectively, as well as the impacts in Well-to-Wheel stage, which refers to the flight operation stage of UAV.

The data used to conduct the life cycle impact assessment on UASs are provided by airworthiness engineers in EHang and published literature. The models applied to the assessment on Falcon L are derived from Stolaroff et al.'s study on battery-powered multi-copter drones used for package delivery (Stolaroff, et al., 2018), and models applied to the assessment on EH216 are derived from Andŕe's study on battery-powered multi-rotor eVTOL vehicles (André, 2022). The models are extensively elaborated in Chapter 3.3.1, Chapter 3.3.5, and Chapter 3.3.6.

There are three approaches proposed to address uncertainties in LCA: the scientific approach, the social approach, and the statistical approach (Finnveden, et al., 2009). The scientific approach suggests handling the uncertainties with improving model accuracy and data quality and the social approach suggests involving stakeholders in discussions to improve the model quality with reinforced data input, processing, and output. Since for the limited data resources and the intention to avoid involving subjective opinions, the statistical approach, which suggests using Monte Carlo experiments with statistical distributions within parameter ranges to account for uncertainties, is applied to this LCA study (Hauschild, Rosenbaum, & Olsen, 2018).

3.3.1 Cradle-to-Grave Assessment Model

This chapter condenses the Cradle-to-Grave environmental impact assessment of UASs, excluding the Well-to-Wheel stage, into material sourcing and production stage and end-of-life stage.

The lifecycle of a UAS is segmented into the lifecycles of the materials comprising its primary components. It is assumed that UAS's total emissions throughout those lifecycles approximately equate to the carbon emissions generated during the production and end-of-life stages of these materials (E_{CO2}^{CTG}). The Cradle-to-Grave CO_2 impact of the aircraft main body except for the battery assembly is calculated by aggregating the result of multiplying the mass (m_i) of each aircraft component, the CO_2 factor of the employed materials (ξ_{CO2}^{i}), and a supplementary factor (μ_i), which is an adjustable factor considering the end-of-life handling impacts for each component. Especially, CO_2 impact of the battery assembly should be modified to consider the CO_2 factor of a type of battery ($\xi_{CO2}^{battery}$), multiplied by the corresponding battery capacity (C), and the supplementary factor (μ) to account for its end-of-life handling impacts. E_{CO2}^{CTG} is represented by the equation:

$$E_{CO2}^{CTG} = \xi_{CO2}^{battery} * C * \mu + \sum_{i} \xi_{CO2}^{i} * m_i * \mu_i. \quad (1)$$

3.3.2 Cradle-to-Grave Assessment on Falcon L

Data. Falcon L is a small electrical Unmanned Aerial System (UAS) designed for efficient and reliable package delivery. Featuring a lightweight design, the aircraft has an unloaded weight of 11.5 kg, which comprises a 4.4 kg Lithium-Polymer (LiPo) battery assembly. The battery assembly includes one battery pack set with 15000 mAh and nominal 45.6 voltage.

The material specifications are detailed in Table 1 for a comprehensive understanding of the required data inputs for this Cradle-to-Grave environmental impact assessment of Falcon L, which excluded the flight operation stage, also called Well-to-Wheel stage. The environmental impact assessment throughout Well-to-Wheel stage is especially discussed in Chapter 3.3.4.

The Falcon L's construction features a variety of materials to optimize performance and durability. The airframe and propellers are primarily composed of carbon fiber reinforced composite, weighing 5.01 kg. Electronics, including motors, circuit boards, sensors, and microcontrollers, account for roughly 1.00 kg of the total weight. Brackets, heatsinks gears and screws are predominantly made of metal alloys, which consist mainly of aluminum, contributing around 1.09 kg, while the other unclear components, amounting to 0.39 kg. The composition and masses of the materials used in battery packs, airframes, and propellers are provided by the in-house engineers. The information for the remaining components is assumed based on literature and traditional drone design.

The end-of-life processing approach will influence the CO_2 emission factors of materials. Different approaches would increase or even decrease the carbon impacts during the production process. For example, if the landfilling or some other disposal approaches are applied, the CO_2 emissions would increase, but if innovative recycling processes conducted or by-products are produced, the emissions might decrease. Even more, with technological development, the production emission of certain materials could be totally compensated. Thereby, the supplementary factor depends on the specific end-of-life processing approaches and with high uncertainties. In this study, the supplementary factor for counting the end-of-life processing influence of carbon fiber reinforced composite is set with range from 0.7 to 1.4. The factors of other components of the aircraft are set with 0.9 to 1.1. Some of these factor settings are suggested by the relevant literature. For example, Kallitsis et al. suggested that the recycling or reusing of battery could possibly reduce its 5% to 15% climate change influence (Kallitsis, Korre, & Kelsall, 2022) and Das suggested that the advanced carbon fiber's disposal stage could mitigate 30% of its carbon effects (Das, 2011).

Within the production stage of Falcon L, materials beyond those listed may be present. However, by focusing on materials with significant mass proportions or high CO_2 emission factors and incorporating statistical variations, the effects of omitted materials are anticipated to be inconsequential.

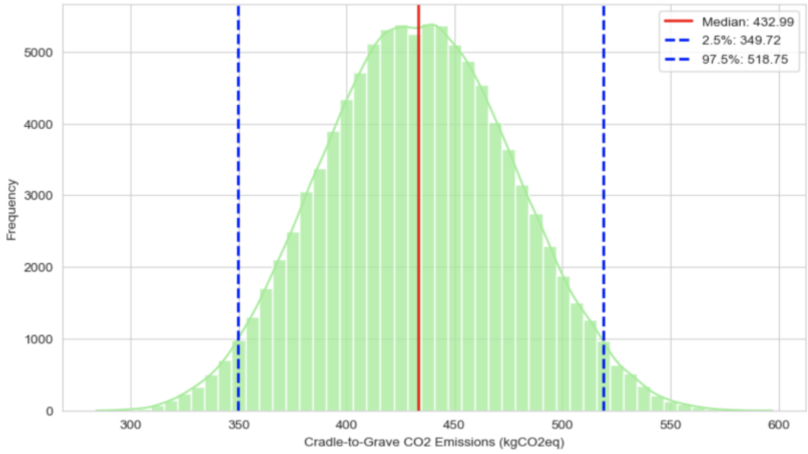
Table 1: Material composition of Falcon L and CO_2 emission factors of materials

System	Battery assembly	Airframe including cargo compartment			
Component	Battery packs	Airframe and Propellers	Motors, circuit boards, sensors, microcontrollers	Brackets, heatsinks, etc.	Others
Material	Lithium-Polymer	Carbon fiber reinforced composite	Electronics	Aluminum	Polymers
Material Mass (m_i) [kg]	4.40	5.01	1.00	1.09	0.39
CO_2 Factor (ξ^i_{CO2})	70-98 g CO_2eq/Wh*	28-35 kg CO_2eq/kg	100-273 kg CO_2eq/kg	8.3-28 kg CO_2eq/kg	2.6-8.3 kg CO_2eq/kg
Supplementary factor (μ_i)	0.9-1.1	0.7-1.4	0.9-1.1	0.9-1.1	0.9-1.1
Reference	(Vandepaer, Cloutier, & Amor, 2017)	(Das, 2011)	(Andersen, Hille, Gilpin, & Andrae, 2014)	(Wernet, et al., 2016)	(Ashby, 2012)

** The CO_2 factor of the battery packs is 70 98 g CO_2eq/Wh and the battery capacity is 684 Wh, so the CO_2 factor of the battery packs is 11 15 kg CO_2eq/kg.*

Results. For calculating the Cradle-to-Grave CO_2 emissions of Falcon L, Monte Carlo simulations and a triangular distribution are adopted to handle uncertain parameters. Ten thousand random samples are generated from the simulation and the result distribution is shown in Figure 9. The simulation results ranging from around 350 to 520 kg CO_2eq and the expected emissions for sourcing and producing the drone were 430 kg CO_2eq.

Figure 10 illustrates the component's contribution to the Cradle-to-Grave CO_2 emissions. In Figure 10, the meaning of these simulation samples is used to calculate the percentages. The Electronics systems were found to be the largest contributor to the emissions, accounting for 77.8% of the total emissions, though their mass contribute just around 10% to the total. The Airframe and Propellers were the second largest contributor, accounting for 38.7% of the total emissions. LiPo Battery Packs were the third largest contributor, accounting for 13.3% of the total emissions, which is close to the percentage number mentioned by the literature (Kallitsis, Korre, & Kelsall, 2022).



Counts	Mean	Standar Dev	2.5%	25%	50%	75%	97.5%
100000.0	433.27	43.81	349.72	402.53	432.99	463.64	518.75

Figure 9. Result distributions of Cradle-to-Grave CO_2 emissions (Falcon L).

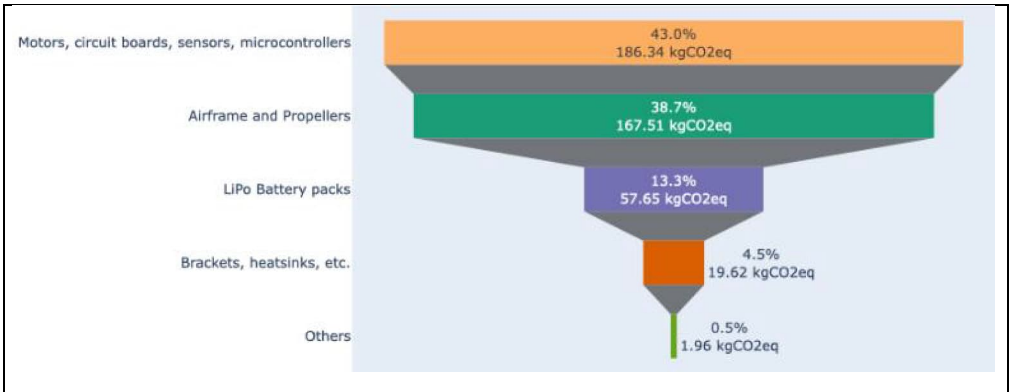


Figure 10. Percentage contributions to total Cradle-to-Grave CO_2 emissions (Falcon L).

3.3.3 Cradle-to-Grave Assessment on EH216

Data. EH216 is a remotely piloted battery-powered vertical take-off and landing rotorcraft, which is able to load 2 passengers onboard. It is a medium-size wingless eVTOL. The multi-rotor configuration has 16 fixed-pitch propellers and 16 units of synchronous motors function as the Distributed Electric Propulsion system. 16 sets of Lithium-Polymer (LiPo) battery packs are equipped to power its flight.

Table 2 listed the material composition of EH216 and CO_2 emission factors of listed materials. The Lithium-Polymer battery assembly equipped with EH216 weighs 184 kg. The battery assembly includes 16 units battery packs, each of them are set with 23,600 mAh and nominal 83.6 V/unit voltage. The airframe and propellers are primarily composed of carbon fiber reinforced composite, amounting to 93.08 kg. The motors mainly consist of permanent magnet materials, contributing 90.96 kg to the total weight. The avionics and control system are a combination of approximately 30% metal alloys, contributing 3.59 kg, and 70% electronic components, contributing 8.37 kg. Similar to the treatment for Falcon L, the effects of materials that EH216 is composed of beyond those listed are anticipated to be inconsequential. The composition and masses of the materials used in battery packs, airframes and propellers, and motors are provided by the in-house engineers. The information for the remaining components is assumed based on literature and traditional eVTOL design.

Table 2: Material composition of EH216 and CO_2 emission factors of materials

System	Battery assembly	Airframe including compartment			
Component	Battery packs	Airframe and propellers	Motors	Avionics and control system	
Material	Lithium-Polymer	Carbon fiber reinforced composite	Permanent magnet	Aluminum	Electronics
Material Mass ($\boldsymbol{m_i}$) [kg]	184	93.08	90.96	3.59	8.37
CO_2 Factor (ξ_{CO2}^i)	70-98 g CO_2eq/Wh*	28-35 kg CO_2eq/kg	75-89 kg CO_2eq/kg	8-28 kg CO_2eq/kg	100-273 kg CO_2eq/kg
Supplementary factor (μ_i)	0.9-1.1	0.7-1.4	0.9-1.1	0.9-1.1	0.9-1.1
Reference	(Vandepaer, Cloutier, & Amor, 2017)	(Das, 2011)	(Wulf, Zapp, Schreiber, Marx, & Schlör, 2017)	(Wernet, et al., 2016)	(Andersen, Hille, Gilpin, & Andrae, 2014)

* *The CO_2 factor of the battery packs is 70-98 g CO_2eq/Wh and the battery capacity is 32 kWh, so the CO_2 factor of the battery packs is 12-17 kg CO_2eq/kg.*

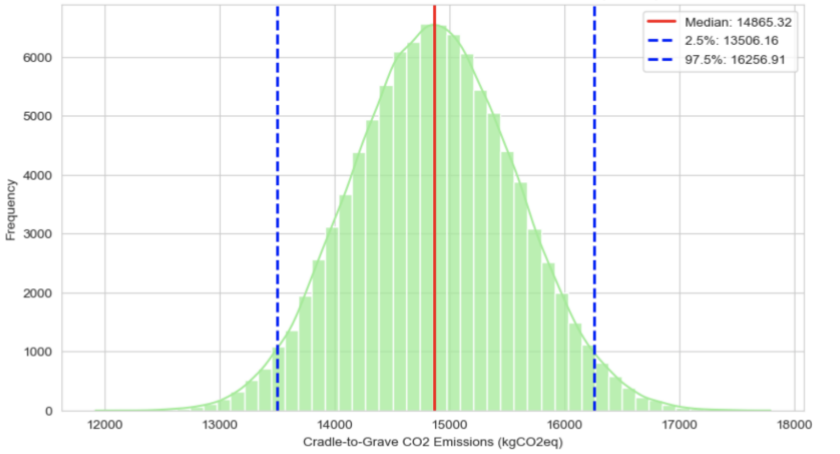
Results. The methodologies are applied to EH216 to calculate its Cradle-to-Grave CO_2 emissions are same as Falcon L. The result distribution is shown in Figure 11. The simulation shows that the expected emissions for sourcing and producing EH216 were 14,900 kg CO_2eq, with emissions ranging from around 13,500 to 16,300 kg CO_2eq.

It is noteworthy that the level of emissions resulting from battery production is consistent with the findings reported in the extant literature. Specifically, the 16-unit LiPo battery packs that are integrated within the EH216 have a total capacity of approximately 32 kWh, and the total emissions associated with their sourcing and production are estimated to be approximately 2,660 kg CO_2eq. In comparison, research has indicated that the CO_2 emissions stemming from the production of three distinct types of 28 kWh lithium-ion batteries (LIBs) range from 2,700 to 3,060 kg CO_2eq (Koroma, et al., 2022). Given that LiPo batteries are known to be more environmentally sustainable than LIBs, the emission results obtained in the present study are consistent with expectations.

To better understand the contributions of each component to the emissions, Figure 12 illustrates the component-wise distribution of Cradle-to-Grave CO_2 emissions. The meaning of the simulation samples is used to calculate the percentages. The results indicate that the permanent magnet motors are the largest contributor to the emissions, accounting for 50.2% of the total emissions, The dominant role played by permanent magnet motors can be attributed to their high carbon emission factor and their substantial mass. The Airframe and Propellers are the second largest contributor, accounting for 20.9% of the total emissions. The 16-unit LiPo Battery Packs are the third largest contributor, accounting for 17.9% of the total emissions, and the avionics and control system accounts for 10.9% of the total emissions.

The dominant role of these motors in emission generation can be traced back to various factors involved in their production process. The upstream steel manufacturing process, which is energy-intensive and has a high carbon emission factor, is the primary contributor to permanent magnet motor's emissions. Then the production processes of aluminum for motor housings and copper for windings comes to the second contributor of the total motor production emissions. The whole production processes also require significant amounts of electricity, often sourced from fossil fuels, further increasing the motor' carbon footprint (Nordelöf, et al., 2019).

It is imperative to underscore that the analytical model in this chapter solely includes the Cradle-to-Grave emissions attributable to the sourcing and producing of a single battery assembly. However, throughout the aircraft's entire lifecycle, the battery system's inherently limited charging and discharging cycles may necessitate periodic replacement. The frequency with which the battery system must be replaced is contingent upon the frequency of recharging cycles. This is inherently influenced by the operational frequency of passenger-transporting flights at a given vertiport. The assessment of flight operations at a vertiport is a multifaceted analysis, which encompasses various factors such as use cases, vertiport network infrastructure, and air traffic logistics systems. A more system-level analysis is presented in Chapter 4, where a detailed exploration of specific use cases, elucidating the potential scenarios and complexities associated with determining the frequency of UAM flight operations within a lifecycle viewpoint.



Counts	Mean	Standar Dev	2.5%	25%	50%	75%	97.5%
100000.0	14869.17	704.64	13506.16	14386.12	14865.32	15349.1	16256.91

Figure 11. Result distributions of Cradle-to-Grave CO_2 emissions (EH216).

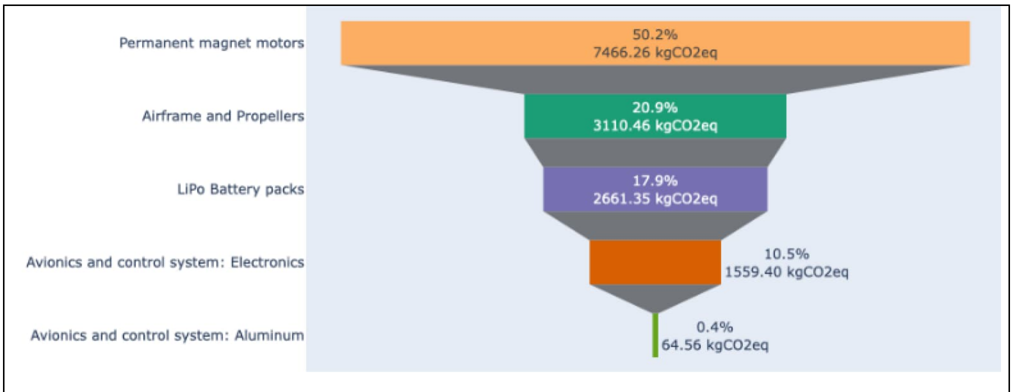


Figure 12. Percentage contributions to total Cradle-to-Grave CO_2 emissions (EH216).

3.3.4 Energy Consumption and Carbon Dioxide Emission

In this chapter, a Well-to-Wheel assessment of UASs is carried out, evaluating the environmental impacts across the flight operation stage, which is also called Use Phase in the LCA framework issued by ISO14040/14044: 2006.

The UAS flight operation stage CO_2 emissions originate from upstream energy systems, involving various stages of energy transmission with potential losses. To assess the energy consumption of a UAS flight, it is essential to trace back the energy transmission flow from the UAS's final consumption to the initial electricity generation. Figure 13 provides a visual representation of the upstream energy flow, illustrating the process from electricity sourcing to the propulsion of the aircraft via its motor system.

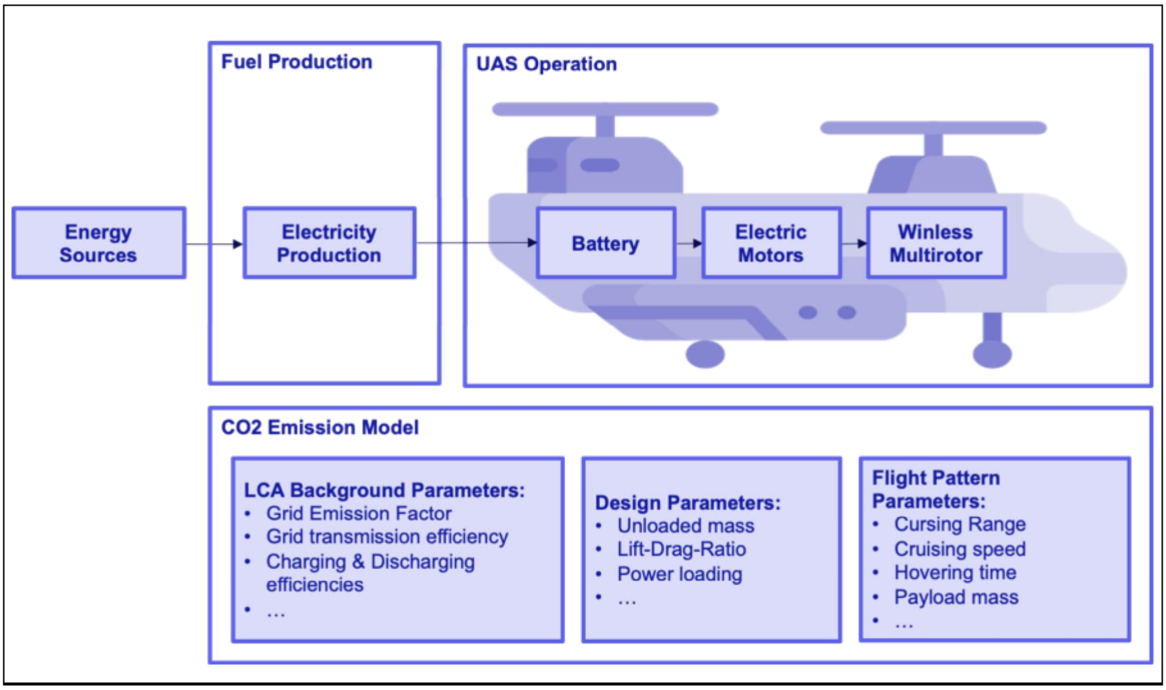


Figure 13. CO_2 emissions sources of the UAS flight operations and the CO_2 model parameters.

Beginning with the wingless multi-rotor, the energy is used by electric motors to power the UAS. The energy transmitted to the motors has already experienced losses due to the efficiency of the propulsion system, which converts electrical energy into mechanical energy for flight. Next, the battery system plays a critical role in storing and supplying the required energy. However, battery charging and discharging processes are not perfectly efficient, leading to energy losses. It is necessary to account for these losses when calculating the actual electricity consumption of the UAS flight. Finally, the electricity production and distribution stages contribute to the overall energy loss. The grid transmission efficiency affects the amount of energy that ultimately reaches the UAS, as some energy is lost during transmission from power plants to the charging points (Stolaroff, et al., 2018).

Considering the losses throughout the energy transmission flow, the total electricity generated to support a UAS flight is higher than the UAS's actual energy consumption. By factoring in the efficiencies of grid transmission, battery charging and discharging, and propulsion systems, the overall CO_2 impacts of UAS flight operations in relation to the upstream energy systems could be quantified.

Other than the LCA background parameters discussed above, estimating CO_2 emissions necessitates data inputs for calculating energy consumption. These inputs are determined by factors related to aircraft design and flight pattern settings. Aircraft design parameters, such as aircraft's mass, the lift-drag-ratio, and some other physics characteristics, determine the energy consumption level of the aircraft. An aircraft's aerodynamic efficiency, structural design, and propulsion system directly impact the energy required to maintain its flight. Flight pattern settings, such as cruising range, flight speed, hovering speed, and other operational choices, also influence energy consumption. These settings depend on how operators configure the aircraft to meet specific mission requirements. For instance, higher flight speeds, longer cruising ranges, or heavier payloads may increase energy consumption.

Conceptual energy consumption models have been developed for both Falcon L and EH216, drawing upon the research conducted by Stolaroff et al. (Stolaroff, et al., 2018) and Andŕe (André, 2022), respectively. Stolaroff et al.'s study offers insights into the energy consumption patterns of a specific type of battery-powered multi-copter drone used for package delivery. The drone's design parameters are similar to Falcon L, making it a suitable reference for creating the Falcon L energy consumption model. Similarly, the EH216 model is developed based on Andŕe's study since for the similar characteristics of the adopted aircraft design.

3.3.5 Well-to-Wheel Assessment on Falcon L

Model: The Falcon L's CO_2 emission generated in Well-to-Wheel stage is

$$E_{CO2}^{WTW} = \frac{\xi_{CO2}^{grid} P_{WTW}^{FalconL}}{\eta_{grid}\eta_{chg}\eta_{dis}\eta}, \tag{2}$$

where ξ_{CO2}^{grid} represents the carbon intensity of a given energy grid, quantifying the amount of carbon dioxide emissions in grams associated with the generation of each kilowatt hour (kWh) of electricity. The carbon intensity data utilized in this study have been sourced from the publicly available platform, Electricity Maps (Electricity Maps, 2023), with the average carbon intensity values observed during the year 2022 being selected for this analysis. The grid transmission efficiency is denoted as η_{grid}, the electricity charging efficiency is denoted as η_{chg}, the electricity discharging efficiency is denoted as η_{chg}, and the battery and motor power transfer efficiency is denoted as η. With forward flight, the Well-to-Wheel energy consumption model applied to Falcon L is represented by the mathematical formula. The power required for steady drone flight package-kilometer traveled ($P_{WTW}^{FalconL}$) can be calculated as

$$P_{WTW}^{FalconL} = \frac{T(v_a sin\alpha + v_i)}{p v_a}, \tag{3}$$

where v_a represents the airspeed, while p denotes the number of package(s). In this study, the influence of wind speed is ignored so airspeed equals the nominated cruising speed. Thrusts produced by Falcon L are approximately equal and collectively counterbalance the forces of gravity and drag forces. Thereby thrust T equals to the numerical sum of Falcon L's total weight (W) and drag force (F_{drag}). It is important to note that these are not vector quantities but parallel forces, which undergo a straightforward numerical addition. Thrust T is given by

$$T = W + F_{drag}. \tag{4}$$

The total drone's weight, denoted as W, is represented by the following equation:

$$W = \sum_{k=1}^{3} m_k g, \tag{5}$$

where g is the gravitational constant, m_k is the mass of the k^{th}component. In this study, m_1, m_2, and m_3, are the masses of the Falcon L's airframe, battery assembly, and payload (when the aircraft is empty, m_3=0), respectively.

The total drag force, denoted as F_{drag}, is given by

$$F_{drag} = \frac{1}{2}\rho \sum_{k=1}^{3} C_{D_k} A_k {v_a}^2, \tag{6}$$

where ρ denotes the air density. The drag coefficient and the projected area of the k^{th} component is represented by C_{D_k} and A_k, respectively. In this study, the drag coefficient C_{D_k} and projected area A_k are determined by three components: Falcon L's airframe, battery assembly, and payload. The numbers of drag coefficients and projected areas for each component are derived from relevant literature sources.

Induced velocity is the downward airflow created by a rotor to generate the required thrust for lifting or propelling an aircraft. To generate lift, the rotor accelerates air downward, creating a pressure difference between the upper and lower surfaces of the rotor. This pressure difference results in an upward force, which is the thrust that supports the aircraft's weight and overcomes any drag forces (Yun, et al., 2007). In the context multirotor UASs, induced velocity v_i is a critical factor in determining the rotor's performance and efficiency. The induced speed v_i is calculated as

$$v_i = \frac{2T}{\pi n D^2 \rho \sqrt{(v_a cos\alpha)^2 + (v_a sin\alpha + v_i)^2}}, \tag{7}$$

where ρ denotes the air density, n denotes the number of rotors ($n = 8$ in this case since Falcon L is an octocopter), D denotes the diameter of Falcon L's rotor blades, and α denotes the angle of attack. In the context of electric UASs or drones, the angle of attack refers to the angle between the rotor plane and the airspeed of the entire drone. Maintaining an optimal angle of attack is essential for achieving efficient and stable flight. The flight control system, combined with the drone's aerodynamic design and motor control, works to maintain an appropriate angle of attack for the rotor blades throughout various flight conditions, such as hover, climb, descent, or forward flight (Yun, et al., 2007). For constant velocity horizontal flight, the angle of attack α is calculated by

$$\alpha = tan^{-1}(\frac{F_{drag}}{W}) . \tag{8}$$

Data. Parameters for assessing the CO_2 impact of Falcon L are shown in Table 3. The values presented in the table are used to assess the CO_2 impact in the two base cases. These cases are defined by specific flight profiles, with the first one being a flight from the start point to the destination while carrying the maximum payload of 5.5 kg that the Falcon L can accommodate. The second case involves a flight back from the destination to the start point, without any payload. The Projected Area and Drag Coefficient values for the airframe, battery, and payload components have been obtained from a previous study (Stolaroff, et al., 2018) that investigated a similar drone configuration. Similarly, the efficiency values are taken from an LCA study (André, 2022). The remaining data inputs were provided by in-house engineers.

Table 3: Base case parameter values used in the Falcon L's Well-to-Wheel CO_2 model

Parameters	Notations	Falcon L
Air Speed [m/s]	v_a	10
Mass of airframe [kg]	m_1	7.1
Mass of battery assembly [kg]	m_2	4.4
Mass of payload [kg]	m_3	{5.5, 0}
Number of Package(s)	p	1
Projected area of airframe [m^2]	A_1	1.49
Projected area of battery [m^2]	A_2	1
Projected area of payload [m^2]	A_3	2.2
Drag coefficient of airframe	C_{D_1}	0.224

Drag coefficient of battery	C_{D_2}	0.015
Drag coefficient of payload	C_{D_3}	0.929
Air density [kg/m^3]	ρ	1.225
Gravitational constant [m/s^2]	g	9.807
Number of rotors	n	8
Diameter of Falcon L's rotor blades [m]	D	0.4826
Battery and motor power transfer efficiency (Electric powertrain efficiency)	η	0.90
Grid transmission efficiency	η_{grid}	0.97
Electricity charging efficiency	η_{chg}	0.98
Electricity discharging efficiency	η_{dis}	0.95

Base Case Results. The base-case flight profile settings specified in Table 3 require the Falcon L to fly directly from its starting point to the destination without any deviations, while maintaining a constant air speed of 10 m/s, which is the drone's maximum speed. This study aims to investigate the drone's CO_2 emission impacts of four cities across Europe: Kassel in Germany, Luxembourg City in Luxembourg, Helsinki in Finland, and Stavanger in Norway. To represent the carbon intensity levels of these cities, the study uses the average values observed in the respective energy grids at the country level. Therefore, Figure 14 depicts the four countries, Germany, Luxembourg, Finland, and Norway, in the figures as a proxy for the carbon intensity levels of the four target cities. A more detailed case study carried out in the four target cities to investigate the specific EMS use cases is presented in Chapter 4.

With the base-case settings, the Well-to-Wheel power consumption of Falcon L is around 0.11 kWh/km with 5.5 kg payloads in the flight. However, the Well-to-Wheel CO_2 emissions vary considerably due to the varying grid CO_2 intensities across different countries. In Germany, which has the highest carbon intensity level of 553 g CO_2eq/kWh, Falcon L generates 74.4 g CO_2eq per package-kilometer traveled. Conversely, in Norway, with a carbon intensity of 41 g CO_2eq/kWh, which shows the predominant reliance on low-carbon energy sources in this country, the drone's emissions are significantly lower at 5.52 g CO_2eq per package-kilometer traveled.

When operating without any payload, Falcon L's well-to-wheel power consumption decreases to around 0.09 kWh/km. Given the same power consumption level, the amount of CO_2 emissions is influenced solely by carbon intensity levels, assuming that energy loss rates remain unchanged. It is beneficial to transition to cleaner energy sources in mitigating the environmental impacts of drone-based delivery systems.

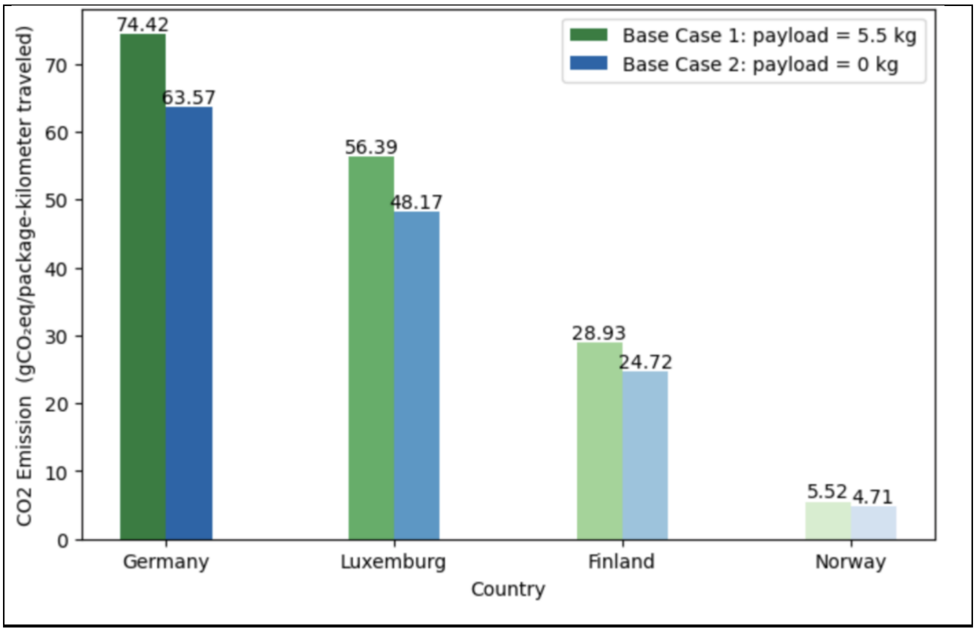


Figure 14. Base cases: Well-To-Wheel CO_2 emissions in different regions (Falcon L).

The two base cases serve as a benchmark for evaluating the Well-To-Wheel CO_2 emissions of the Falcon L drone in comparison to other modes of transportation when interpreting the results. This comparison with other forms of mobility is discussed in Chapter 3.3.7.

Sensitivity Analysis. The sensitivity analysis is conducted to explore how the Well-To-Wheel CO_2 emissions of the Falcon L vary as different input variables are changed. This analysis considers five key variables, including grid carbon intensity, air speed, payload mass, electric powertrain efficiency, and grid transmission efficiency.

Table 4: Sensitivity analysis variable settings for Well-To-Wheel CO_2 emissions (Falcon L)

Variable	Notations	Min	Max	Increment
Carbon emissions from the grid (Carbon intensity) [g CO_2eq/kWh]	ξ_{CO2}^{grid}	10	560	50
Air speed [m/s]	v_a	0	10	0.5
Mass of payload [kg]	m_3	0	5.5	0.5

Battery and motor power transfer efficiency (Electric powertrain efficiency)	η	0.9	1.0	0.01
Grid transmission efficiency	η	0.9	1.0	0.01

By systematically altering these variables within specific ranges, as shown in Table 4, their individual and combined effects on Falcon L's overall Well-To-Wheel CO_2 emission impacts the analysis are identified in Figure 15. The analysis results reveal a diverse range of CO_2 emissions, with values spanning from a minimum of 0.59 to a maximum of 81 g CO_2eq per package-kilometer traveled, and an average of 27 g CO_2eq per package-kilometer traveled. The standard deviation of 17 indicates a considerable variation in emissions, which suggests that distinct combinations of input variables can result in substantially different emission levels. This observation underscores the importance of meticulously examining the interplay of these factors in relation to the drone's design and operational profile settings to minimize environmental impact. The sharp curve observed for carbon intensity also emphasizes that a cleaner grid is paramount for more sustainable drone operations.

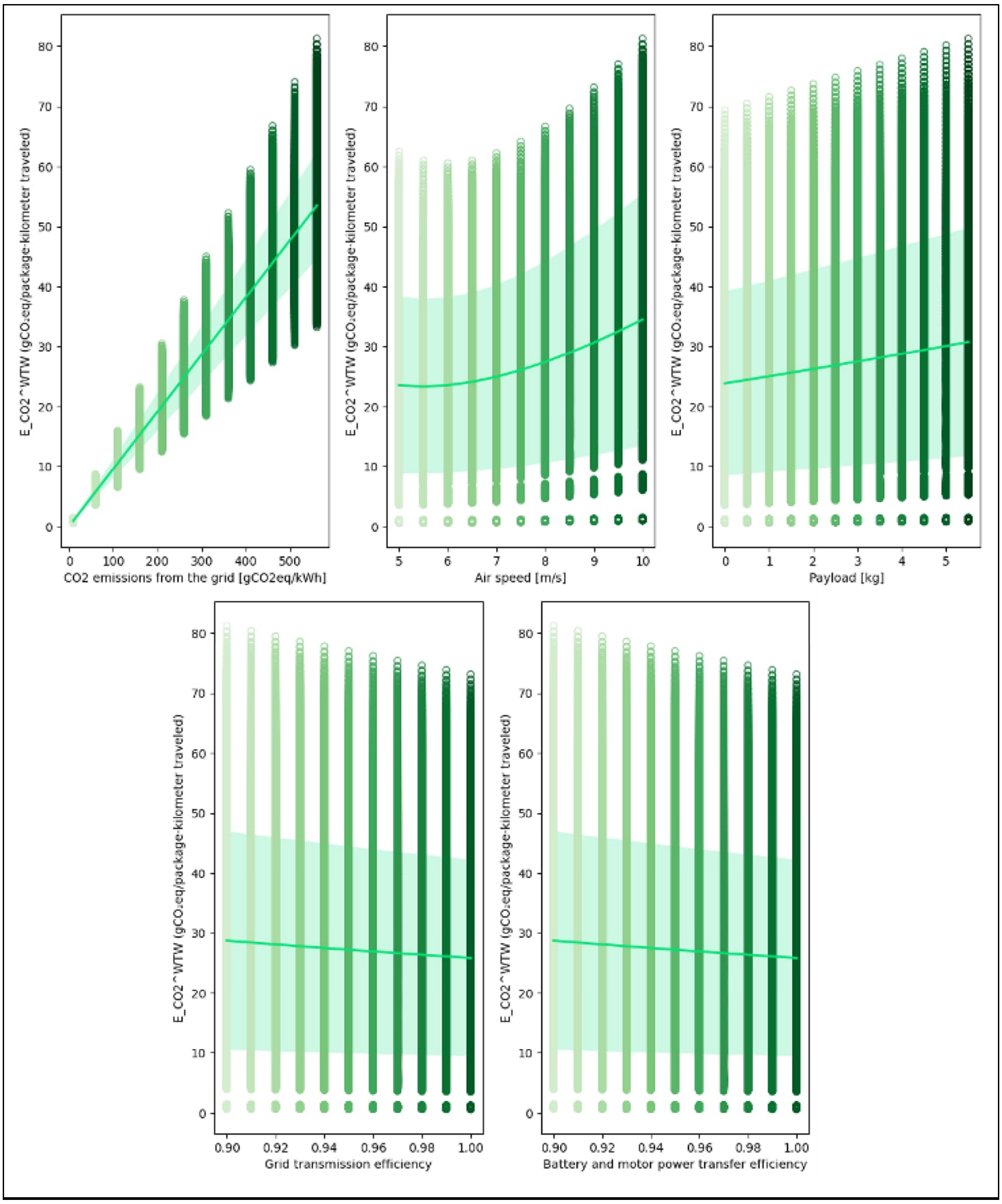


Figure 15. Well-To-Wheel CO_2 emissions of the Falcon L vary as different input variables.

3.3.6 Well-to-Wheel Assessment on EH216

The rotor blades' radius of EH216 is 1.6 m and the cabin of it is designed to contain a maximum of 2 passengers. EH216 is designed to carry one 80 kg passenger at the maximum speed that is around 100km/h over a range of 15 km. With the same speed, the maximum flight range of EH216 could be improved to 35 km when the cabin is empty.

Model. The EH216 CO_2 emission model is same to what is developed for Falcon L. Equation (9) is used to calculate EH216 CO_2 emission, denoted as E_{CO2}^{WTW}:

$$E_{CO2}^{WTW} = \frac{\xi_{CO2}^{grid} P_{WTW}^{EH216}}{\eta_{grid}\eta_{chg}\eta_{dis}\eta}. \tag{9}$$

However, the power required for steady drone flight per meter per passenger P_{WTW}^{EH216} can be calculated using

$$P_{WTW}^{EH216} = \frac{P_{total}}{p * d}, \tag{10}$$

where d represents the cruising distance, while p denotes the number of passenger(s).

The total power required for the flight mission is given by

$$P_{total} = t_{crs}P_{hov} + t_{hov}P_{crs}. \tag{11}$$

The cruising time t_{crs} equals to the flight distance of the mission d divided by the steady cruising velocity v_{crs} then minus the hovering time t_{hov}. The equation is

$$t_{crs} = \frac{d}{v_{crs}} - t_{hov}. \tag{12}$$

The power required for hovering stage and cruising stage is separately measured. The power required for the hovering stage is obtained from

$$P_{hov} = \frac{\sum_{k=1}^{3} m_k g}{PL}, \tag{13}$$

where power loading PL used in the hovering stage is the ratio of the weight of the aircraft to the power produced by the engine or propulsion system. The value of power loading depends on the aircraft's design gross mass, the total disk area of the rotor or propeller disks, and the rotor's figure of merit, which is a measure of the rotor's aerodynamic efficiency (Leishman, 2006). The value of power loading used in this study is from Andŕe's study on electrical quadcopter (André, 2022).

Different with the power required for hovering stage, power required for the cruising stage P_{crs} can be represented in the following equation:

$$P_{crs} = \frac{v_{crs} \sum_{k=1}^{3} m_k g}{L/D}, \tag{14}$$

where lift-to-draft ratio L/D reflects the aerodynamic efficiency of multi-rotor configurations in the cruising stage of flight.

Figure 16 illustrates the simplified flight pattern used in the energy consumption model for EH216. The flight profile of EH216 could consist of five distinct phases: takeoff hover (A to B), climb (B to C), cruise (C to D), descent (D to E), and landing hover (E to F). Each of these phases has unique characteristics in terms of travel time, velocity, and corresponding power consumption, while the model takes solely the power consumption during the hovering and cruising stages of flight into account:

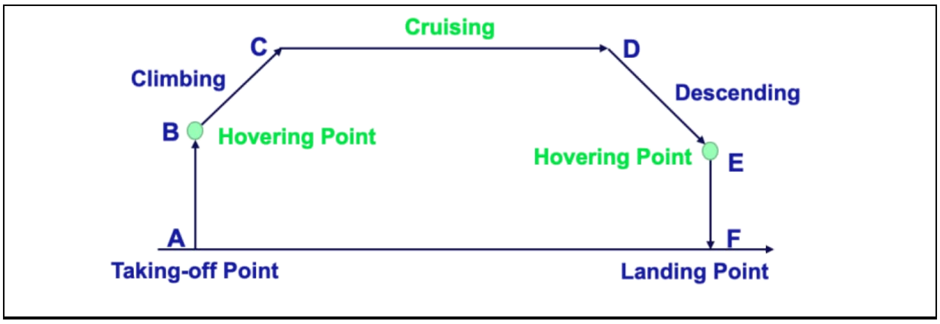


Figure 16. Flight pattern used in the energy consumption model for EH216.

Data. Parameters for assessing the CO_2 impacts of EH216 are shown in Table 5. The number shown in this table is used in the base case CO_2 impact assessment. The base case values of Power Loading and Lift-to-Drag are indicated by Ballo's conceptual study on EH184, which has the similar configuration of EH216 (Ballo, 2020). The base case efficiency values are from a previous study (André, 2022). Other base case data inputs are provided by in-house engineers. Monte Carlo simulation is employed to account for uncertainties in the parameters of Power Loading and Lift-to-Drag Ratio by using statistical distributions within their respective ranges. These simulations involve running multiple iterations with randomly sampled values from the defined distributions.

Table 5: Base case parameter values used in the EH216's Well-to-Wheel CO_2 assessment model

Parameters	Notations	EH216
Cruising velocity [m/s]	v_{crs}	27.78
Flight distance [m]	d	{15,000, 35,000}
Time of hovering [s]	t_{hov}	90
Mass of main body [kg]	m_1	196
Mass of battery assembly [kg]	m_2	184
Mass of passenger [kg]	m_3	{80, 0}
Number of passenger(s)	p	1
Power Loading (N/KW)	PL	108
Lift-to-Draft Ratio	L/D	2.30
Gravitational constant [m/s²]	g	9.807

Battery and motor power transfer efficiency (Electric powertrain efficiency)	η	0.95
Grid transmission efficiency	η_{grid}	0.97
Electricity charging efficiency	η_{chg}	0.98
Electricity discharging efficiency	η_{dis}	0.95

Base Case Results. The base-case flight profile settings specified in Table 5 require the EH216 to fly directly from its starting point to the destination without any detouring in the air, while maintaining a constant air speed of 27.78 m/s, which is the eVTOL's maximum speed. The adoption locations are the same as what are applied to Falcon L.

The findings of the study indicate that when the EH216 operates at its maximum cruising speed while carrying a load of 80 kg (representative of an average adult male) and travels its maximum flight range of 15 km, the power required for the hovering stage is 1.04 kW, and the power required for the cruising stage is 6.81 kWh. The energy consumption per kilometer of travel in this scenario is estimated to be 0.52 kWh/km. In contrast, when the aircraft operates without any passenger load, it can achieve its maximum flight range of 35 km, but requires a higher power during the cruising stage (14.63 kWh), with a lower power required during the hovering stage (0.86 kWh), and the estimated energy consumption per kilometer of travel is 0.44 kWh/km.

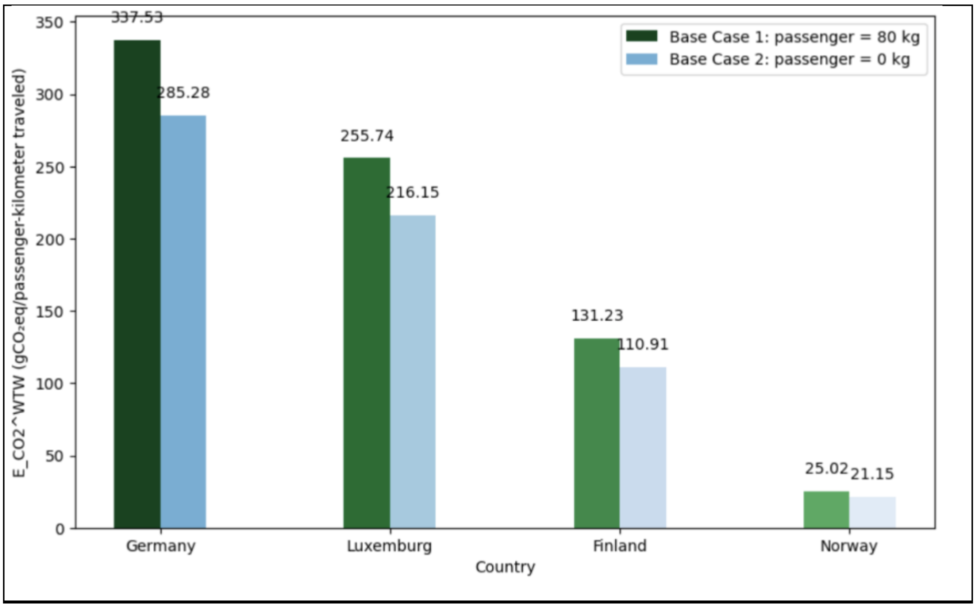


Figure 17. Base cases: Well-To-Wheel CO_2 emissions in different regions (EH216).

Taking into consideration the efficiency of energy distribution, battery charging and discharging, and the aircraft's powertrain transmission, the CO_2 emissions per passenger-kilometer traveled of the EH216 aircraft are ultimately determined by the source-to-usage emissions of electricity generation across different countries. The results of the study are presented in Figure 17.

Sensitivity Analysis Using Monte Carlo simulation. A sensitivity analysis using Monte Carlo simulation is performed to evaluate the impact of different variables for EH216. Uncertain parameters such as the Power loading (PL) and the lift-to-drag ratio (L/D) are simulated with stochastic values by applying Monte Carlo approach. Power loading (PL) ranges from 94 to 122 (André, 2022) and lift-to-drag ratio (L/D) ranges from 1.8 (Brown & Harris, 2020) to 5.3 (Johnson & Silva, 2018), respectively. The ranges are cited from the literature value.

Then the sensitivity analysis is conducted for testing how the changes in hovering time, mass of passenger(s), grid carbon intensities, affect Well-to-Wheel CO_2 emissions. Due to the unavailability of data inputs from the aircraft manufacturer, the correlation function between flight range and passenger mass is unknown. Therefore, this analysis is conducted by using pairs of values to generate multiple combinations of inputs to simulate the Well-to-Wheel CO_2 emissions output using a physics-based model, which could fit with EH216. The combinations of inputs for the sensitivity analysis include three values for hovering time, namely 60, 90, and 120 seconds. The payload mass varies across three values, including 0, 80, and 220 kg. The cruising speed is fixed at a value of 27.78 m/s. The flight range is a human-set variable that is subject to specific limitations. Specifically, when the payload mass is 0 kg, the maximum flight range is observed to be 35,000 m, while the maximum flight range is 15,000 m when the payload mass is 80 kg. The values of grid carbon intensities are set regarding to the nominated cities.

The Frequency histograms in Figure 18 visualize the variability of the Well-to-Wheel CO_2 emission values across different variable combinations by identifying which variables have the significant impact on the emission. It shows that carbon intensities and mass of passenger(s) have a significant impact but hovering time not. Countries with higher carbon intensities, such as Germany and Luxemburg, have higher Well-to-Wheel CO_2 emission values than countries with lower carbon intensities, such as Finland and Norway. Similarly, with the payload mass increasing, the Well-to-Wheel CO_2 emission increase correspondingly.

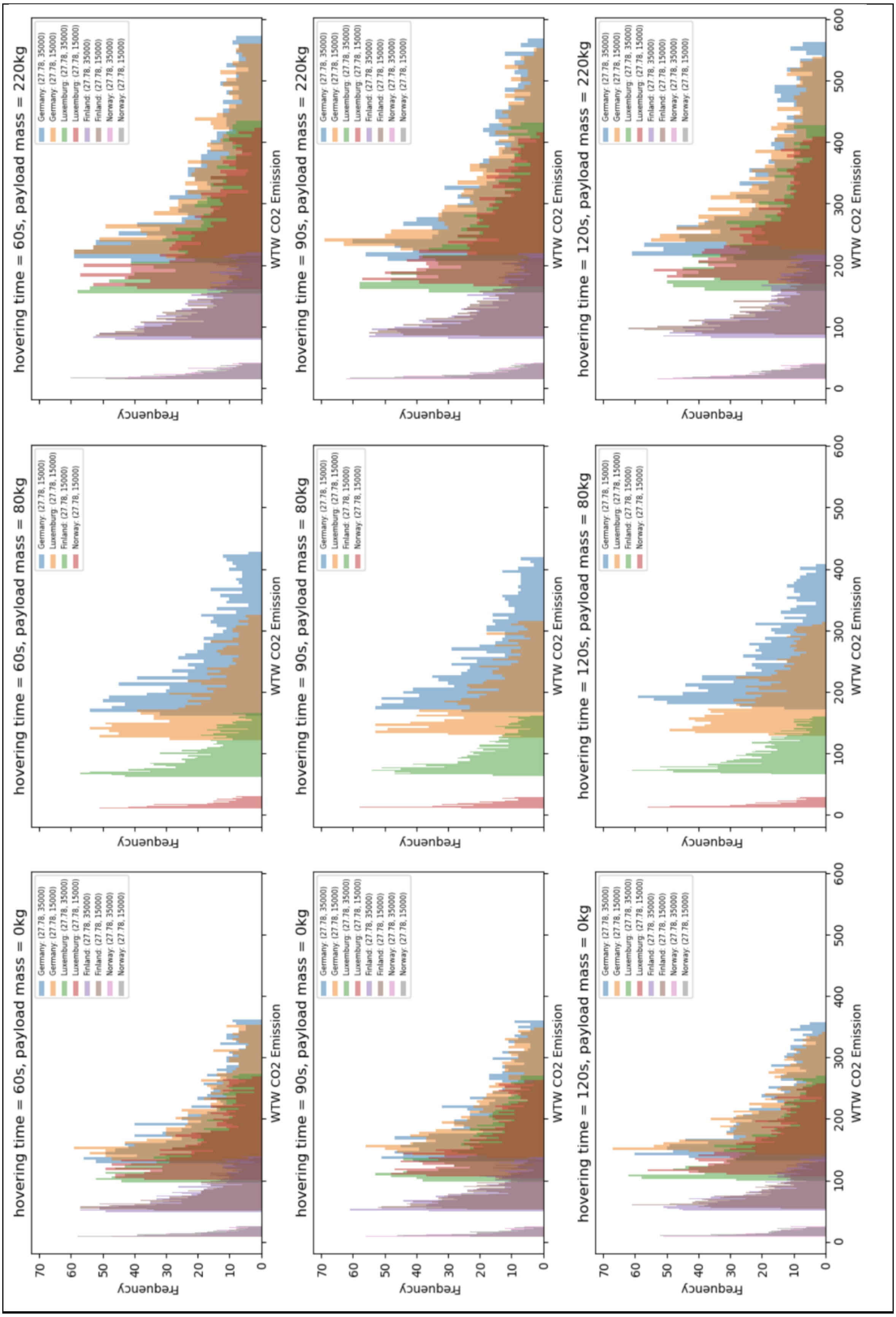


Figure 18. Frequency distribution of WTW CO_2 Emission values of EH216 for each combination of sensitivity analysis variables.

The box plots presented in Figure 19 and the statistical summary Table 6 show the distribution of WTW CO_2 emission values for each country. For instance, the sensitivity analysis reveals that in Finland, the WTW CO_2 emission can range from 50 to 220 g CO_2eq per package-kilometer traveled, with a standard deviation of 35.8. It is noteworthy that the base-case values used for the comparisons with other forms of mobilities in Chapter 3.3.7 in this study are higher than the mean and medium values presented in this sensitivity analysis, indicating the conservative comparison principle applied to this study.

Table 6: Statistical summary of WTW CO_2 emission values of EH216 for each country

WTW CO_2 emission values of EH216 (g CO_2eq per package-kilometer traveled)							
Regions	Mean	Std Dev	Min	25%	50%	75%	Max
Germany	264.53	92.33	129.81	194.21	245.62	314.27	573.94
Luxemburg	201.60	69.34	98.21	148.80	187.95	239.16	435.22
Finland	103.05	35.80	50.44	75.28	96.39	122.36	221.69
Norway	19.62	6.86	9.64	14.30	18.28	23.34	42.69

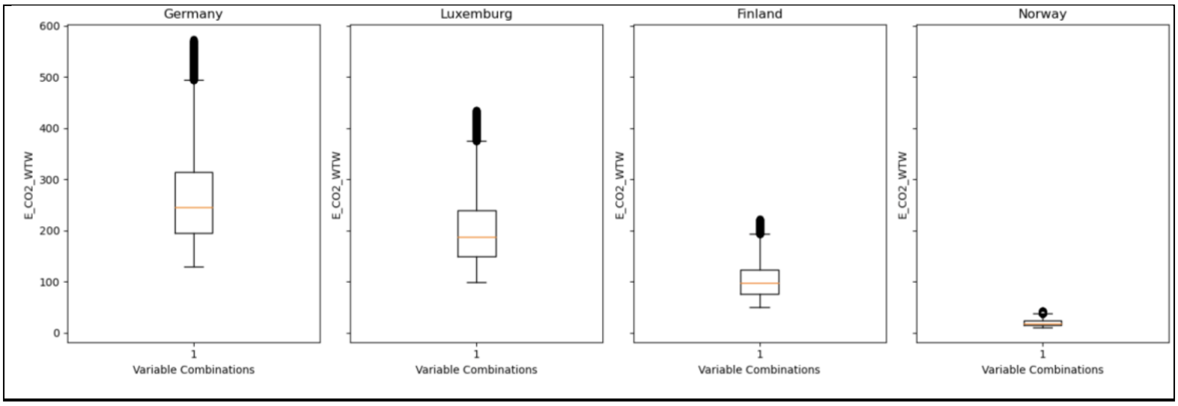


Figure 19. Statistical distribution of WTW CO_2 emission values of EH216 for each country.

3.3.7 Comparing Falcon L and EH216 with Other Modes of Transportation

In this chapter, the energy consumption and CO_2 emissions of various transportation modes are compared. For consistency, the comparison assumes that electric powertrain efficiency and battery charging and discharging efficiency for all listed electric vehicles are the same as those applied to Falcon L and EH216 and the batteries are charged in the grid of Finland.

According to Table 7, electric cargo bicycles have the lowest energy consumption at 0.03 kWh/km, resulting in emissions of 8 g CO_2eq/km (Rodrigues, et al., 2022). Comparatively, the Falcon L consumes more energy at 0.11 kWh/km and produces higher emissions of 29 g CO_2eq/km. Personal electric cars consume 0.28 kWh/km and emit 74 g CO_2eq/km (Stolaroff, et al., 2018), while the EH216 has even higher energy consumption at 0.52 kWh/km and emissions of 131 g CO_2eq/km.

Small electric vans consume 0.47 kWh/km and emit 124 g CO_2eq/km (Rodrigues, et al., 2022), whereas personal cars show a substantial increase in energy consumption at 0.78 kWh/km and CO_2 emissions of 251 g CO_2eq/km (Stolaroff, et al., 2018). Medium-duty e-trucks consume 1.05 kWh/km, resulting in emissions of 278 g CO_2eq/km (Rodrigues, et al., 2022). Diesel vans, which have the highest energy consumption at 2.08 kWh/km, also produce the highest emissions, reaching 12,830 g CO_2eq/km (Figliozzi, 2017).

This comparison provides insights that Falcon L and EH216, while more environmentally friendly than personal cars and diesel vans, exhibit higher energy consumption and CO_2 emissions than electric cargo bicycles and personal electric cars, respectively. This suggests that although UASs show promise as an alternative transportation mode, further improvements in energy efficiency are necessary to make them more competitive with other electric vehicles.

Indeed, the comparison provided in the table is limited to one-to-one delivery scenarios (EMS is one of them) and real-world applications may involve transporting multiple passengers or packages using a single vehicle. As such, the energy consumption and CO_2 emissions per passenger or package can vary significantly depending on the transportation mode and logistics system design. Taking these factors into account, the sustainability nuances of each transportation mode may shift.

Table 7: Energy required per km of travel and CO_2 emissions for different vehicles

Performance Measure	Energy consumed	Emissions in Finland	Reference
Unit	kWh/km	g CO_2eq/km	
Electric cargo bicycle	0.03	8	(Rodrigues, et al., 2022)
Falcon L	0.11	29	
Personal electric car	0.28	74	(Stolaroff, et al., 2018)
EH216	0.52	131	
Small electric van	0.47	124	(Rodrigues, et al., 2022)

Personal fossil fuel cars	0.78	251	(Stolaroff, et al., 2018)
Medium duty e-truck	1.05	278	(Rodrigues, et al., 2022)
Diesel vans	2.08	12,830	(Figliozzi, 2017)

3.3.8 Vertiport System Analysis

Vertiport constructions and operations are expected to have significant impacts on the environment. Although vertiports function as a secondary background system within the broader UAM network, it is still crucial to include them in our analysis due to their predicted substantial contribution (>50%) to overall emissions (Ploetner, et al., 2020).

Accurately evaluating the energy requirements and potential emission sources of vertiports in UAM operations requires a comprehensive analysis and with high uncertainties. The vertiport energy requirement is decided by what kinds of aircraft it serves for, how the UAM "airlines" are designed in the specific scenarios, where the vertiports are located, and what the population characteristics are in that location.

A vertiport represents a complex system characterized by emergent operational behaviors and unpredictable outcomes (Patel, Gunady, Rao, Wright, & DeLaurentis, 2022). Potential uncertainties, such as fluctuating timeframes, the varying maturity of UAM technologies, and a range of adoption scenarios, further complicate the CO_2 emission assessment of vertiport. Even within a specific chosen scenario, factors like local climate, types of fuels or grid energy sources, and manners of operations can lead to significant variability (Schweiger & Preis, 2022). A comprehensive evaluation of vertiport emission sources and operational energy requirements involves examining various infrastructure operations. Except for meeting the regulation standards, a mature vertiport operation could involve various types of operations. These ground operations include lighting, heating, ventilation, and air conditioning (HVAC), maintenance, communicating and monitoring, repair, and overhaul (MRO) services, even tow or tug solutions that transports the aircraft, all of which contribute to electricity consumption. Consequently, given the uncertainties arising from the present ex-ante application time horizon and dynamic contexts, measuring emissions from individual vertiports may yield incomparable and inconsistent results. This inconsistency can be attributed to the multitude of influencing factors, as well as the rapidly evolving nature of UAM technologies and the expansion of infrastructure networks.

For operating UASs in current stage for limited-scale emergency medical services, the vertiport could be equipped simply. On the one hand, the existing ground or rooftop infrastructure such as heliports or helipads used for supporting medical helicopter operations can be deployed for UAS operations either. On the other hand, the compact design of the UASs makes complex ground vertiport unnecessary, allowing for more flexible deployment. The high maneuverability level due to the light and small aircraft design, and the simplified charging system of the UASs bring high-level flexibility to the infrastructure operations. Moreover, in the foreseeable short-term future, UAM will only serve as a supplementary transportation mode in EMS cases, rather than completely replacing existing medical transport systems, such as ambulances. The relatively lower usage frequency and fast on-demand nature of air EMS do not necessitate complex ground airport system designs.

Hence, a hangar, representing the most basic form of a vertiport, proves adequate for accommodating and maintaining UAM vehicles employed in EMS use cases. One-off and short-term CO_2 emissions are associated with construction activities, while long-term emissions persist relatively continuously owing to the recurring nature of flight operation missions.

3.3.9 Vertiport Carbon Dioxide Emission Assessment

This chapter aims to examine the CO_2 emissions generated by both vertiport constructions and operations.

Methods. In this study, carbon emissions generated by the construction and operation of small-size hangars are analyzed in this analysis. The CO_2 emission of vertiport construction is estimated by using industrial data. The CO_2 emission assessment of vertiport operation is simplified, with attention given exclusively to HVAC systems and aircraft charging. It is noted that the carbon emissions attributed to the charging system have already been covered in the Well-to-Wheel flight operation model, thereby obviating the need for duplicative calculations, the energy consumption of the HVAC system is identified as the primary source of energy consumption in the hangar operation emissions.

Results. For the construction CO_2 emission assessment, according to the data provided by the in-house engineers, the equivalent total diameter of Falcon L is 1.4 m and an existing hangar used for one package delivery drone in the EMS sector is around 15 square meters. Industrial data indicates that the environmental impact associated with constructing a steel hangar amounts to 386.55 kg CO_2eq per square meter, while constructing an aluminum hangar results in 309.24 kg CO_2eq per square meter (Gaptek, 2021). Thus, the CO_2 emissions resulting from the construction of a hangar for Falcon L operations range between 4,640 and 5,790 kg CO_2eq. Moreover, it is postulated that a hangar accommodating the EH216 necessitates a minimum of four times the area of a drone hangar, due to its 5-m aircraft diameter and the increased spatial requirements for placement and ground service operations. In accordance with this assumption, the CO_2 emissions for constructing a hangar tailored to EH216 operations vary from 18,550 to 23,220 kg CO_2eq.

The summary of CO_2 emission assessment results are shown in Table 8, Figure 21, and Figure 22, which will be used as the base-case values in the case study conducted in Chapter 4.

Table 8: Hangar construction CO_2 emission assessment results

CO_2 Emissions [kg CO_2eq]	Min	Max
Hangar construction for Falcon L	4,640	5,790
Hangar construction for EH216	18,550	23,220

In the methodology for estimating operational emissions, this study utilizes empirical data on the monthly electricity requirements of a 15-square-meter principal hangar employed in Swedish emergency medical delivery services. Base on the assumption that the HVAC system constitutes the most significant portion of the hangar's electricity consumption, the temperature dynamics and the hangar size are identified as key factors affecting HVAC electricity consumption within the hangar. An exponential model is employed to estimate the electricity consumption of the hangar in the target cities, based on the 40-year historical local temperature data, and under the assumption that the hangar designated for Falcon L maintains the same dimensions across these locations. The predicted energy consumption results for those cities are presented in Figure 20. Based on this prediction, research has revealed a linear correlation between electricity consumption and building area, indicating that the amount of electricity consumption will increase by the same ratio as the building area increase (Malakoutian, Malakoutian, Mostafapoor, & Amjadi, 2021). Hence when a hangar four times larger is deployed for EH216 operations, the energy consumption is projected to be four times greater than that of the hangars for Falcon L operations.

The finding suggests that hangars in the four targeted cities located in Northern areas may generate significantly higher levels of CO_2 emissions during the winter months, specifically December, January, and February, due to the colder temperatures. Based on the findings, potential solutions could be proposed to reduce the carbon footprint of hangars in the winter months, such as implementing energy-efficient heating systems, effective insulations, or reducing the idle time of hangar operations.

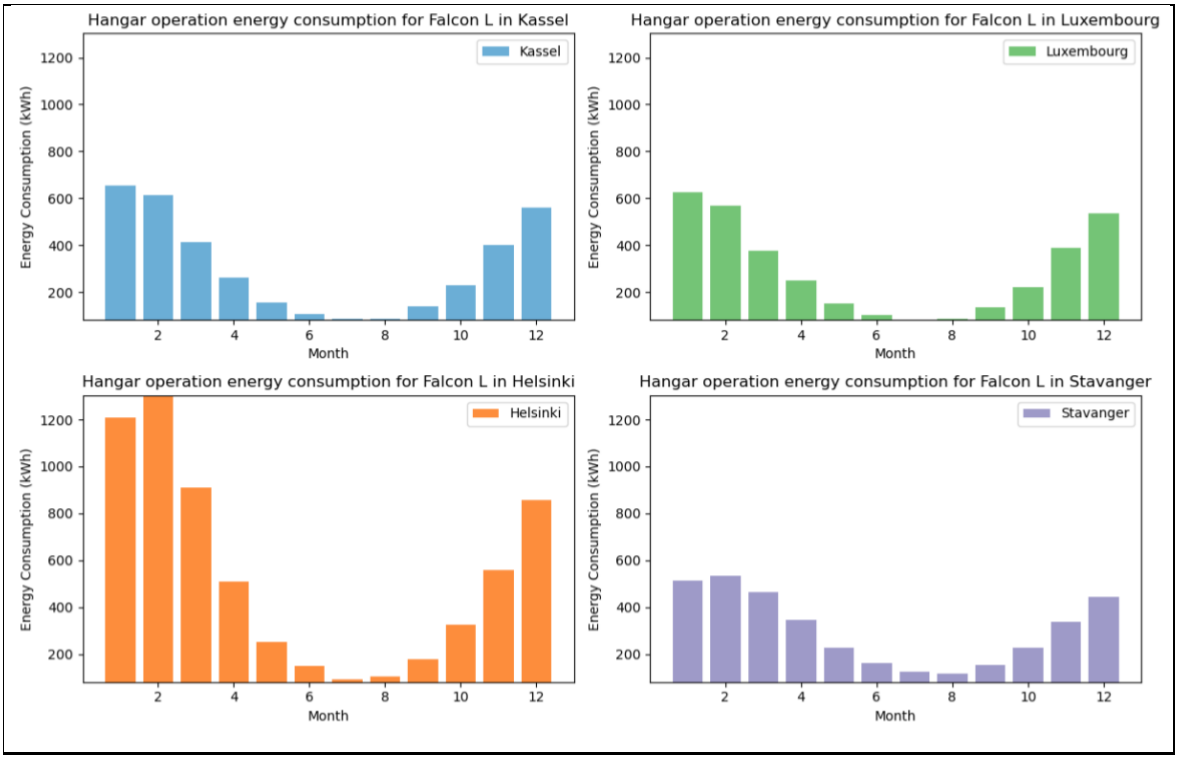


Figure 20. Predicted Falcon L's hangar operation energy consumption for targeted cities.

Figure 21 and Figure 22 presented the CO_2 emission results for both Falcon L and EH216 in targeted regions respectively. It is evident that the monthly CO_2 emissions resulting from hangar operations are amplified by the factors: hangar areas and the emission factor of the city's grid. Notably, a hangar situated in Stavanger, Norway with the cleanest grids, generates significantly lower CO_2 emissions throughout the year, despite having similar monthly energy consumption levels as hangars in Luxembourg and Kassel. Although the electricity consumption of a hangar located in Helsinki could be considerably higher than that of one in Kassel, the resultant CO_2 emissions of a hangar located in Helsinki is obviously lower than that of one in Kassel.

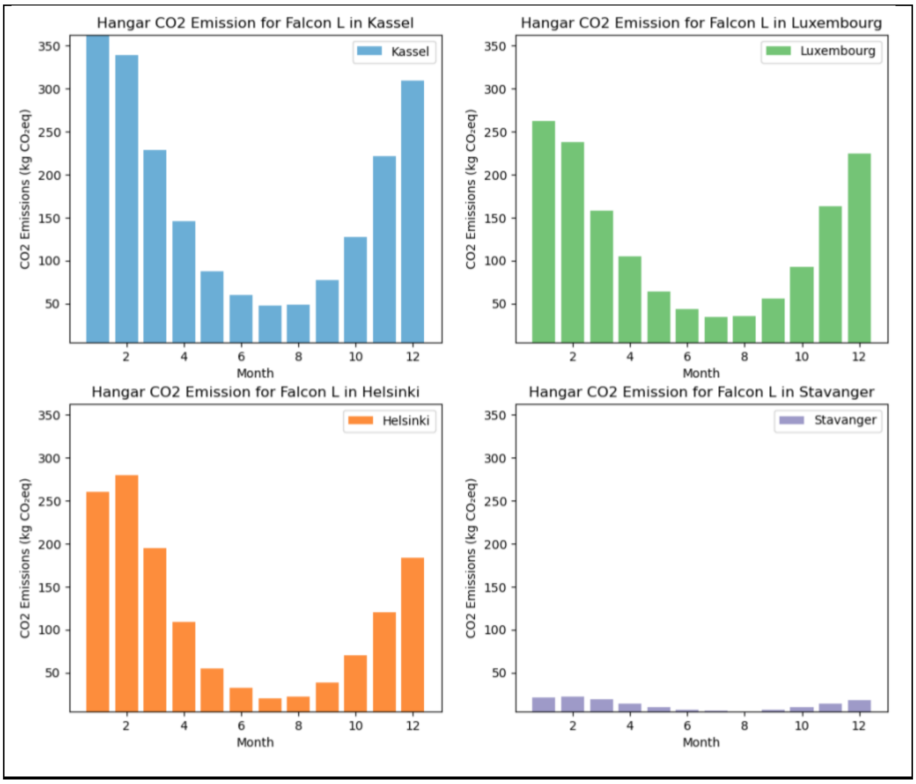


Figure 21. Hangar monthly operation CO_2 emissions for targeted cities (Falcon L).

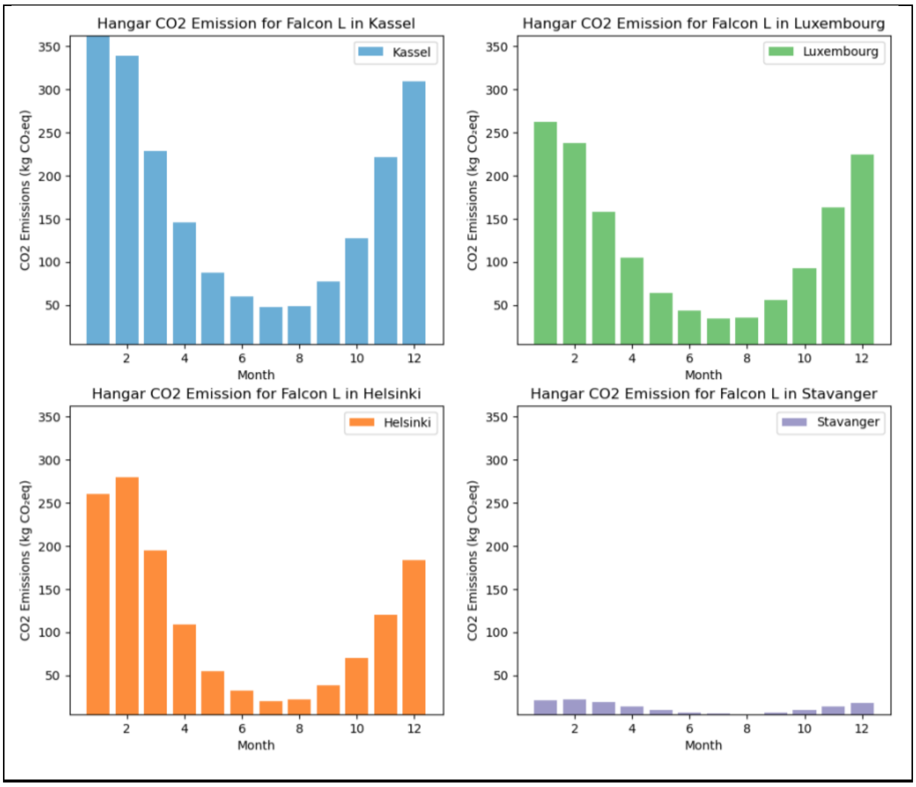


Figure 22. Hangar monthly operation CO_2 emissions for targeted cities (EH216).

4 Urban Air Mobility Case Study in Emergency Medical Service Scenarios

In this chapter, the objective is to evaluate the cumulative lifetime CO_2 emissions of both the Falcon L and EH216. These UASs have been particularly utilized for Emergency Medical Services (EMS) missions starting from early 2022 until the termination of their operational lifespan.

4.1 Case Study Assumptions

A set of assumptions are established as the basis for the case studies. These assumptions encompass four primary dimensions: Life Cycle Assessment (LCA) background assumptions, scenario assumptions, flight assumptions, and vehicle assumptions.

LCA background assumptions include: 1) The electricity grid in each city under consideration remains constant within each year through the lifetime of the UAS but experiences a steady decrease at a specific rate annually. 2) CO_2 factors for materials remain constant throughout the lifetime of the UAS.

Scenario assumptions include: 1) EMS operates 24 hours a day, 7 days a week, and 365 days a year. 2) During the lifetime of the UAS, the demands of UAS emergency medical tasks in each adopted city for each year will not change significantly. 3) The UAS emergency medical tasks are only executed at a feasible time.

Flight assumptions include: 1) The UAS's operation is associated with only one vertiport. 2) The UAS can make only one package delivery or transport a single passenger per trip, and it must return to the vertiport with an empty compartment after each delivery. 3) The loaded mass of the payload (5.5 kg) or passenger (80 kg) remains consistent for all trips throughout the UAS's lifetime. 4) The UAS's battery is capable of powering the entire flight task without requiring recharging during the task. 5) After completing each task, the UAS's battery is recharged and fully prepared for the next task. 6) The UAS's speeds remain constant and adheres to specified values. 7) The flight distance for each task is equal to the maximum flight range of the UAS with the nominal loaded mass. 8) The UAM consumes electricity at a constant rate during flight operations.

Vehicle assumptions include: 1) The UAS would not be broken or malfunction throughout its nominal lifetime. 2) The depreciation of the vehicle does not affect the normal operation or reaching the maximum flight range of the UAS. 3) The battery assembly is assumed to receive proper maintenance, enabling it to function normally throughout its nominal discharging cycles.

4.2 Case Study Model

The model used in this study provides a comprehensive assessment of the environmental impact of an UAS over its lifetime by adding up the CO_2 impacts generated during four different stages: vertiport construction, vertiport operation, aircraft production, and flight operation. The detailed assessment for each component has been covered in Chapter 3. The total lifetime CO_2 emission, denoted as $E_{CO2}^{lifetime}$, is calculated by

$$E_{CO2}^{lifetime} = E_{CO2}^{UAV\ prod} + E_{CO2}^{UAV\ op} + E_{CO2}^{verti\ cons} + E_{CO2}^{verti\ op}, \tag{15}$$

where the total vertiport (or in our case, hangar) construction CO_2 impact $E_{CO2}^{verti\ cons}$ have been previously calculated and are known values obtained from Chapter 3.3.9.

The total vertiport operation CO_2 impact $E_{CO2}^{vertiport\ op}$ can be calculated by summing up the product of energy consumption $P_{i,j}^{verti}$ for month i in year j and the corresponding grid factor for CO_2 emissions in year j per unit of energy consumed $\xi_{CO2_j}^{grid}$. This calculation is done for a period of the UAS's lifetime:

$$E_{CO2}^{vertiport\ op} = \sum_{i,j} P_{i,j}^{verti} * \xi_{CO2_j}^{grid}. \tag{16}$$

The CO_2 emissions generated during the operation of the UAS are calculated by summing up the product of the energy consumption during outbound and inbound flights, the flight distance for each flight task d, the frequency of UAS flights f_{ij} for month i in year j, the corresponding grid factor for CO_2 emissions per unit of energy consumed over a j-year period, which is the UAS's lifetime. This calculation takes into account the entire flight task of the UAS, including the flights from and back to the vertiport. The CO_2 emissions generated during the operation of the UAS, denoted as $E_{CO2}^{UAV\ op}$, is represented by

$$E_{CO2}^{UAV\ op} = \sum_{i,j} (P_{outbound}^{WTW} + P_{inbound}^{WTW}) * d * f_{ij} * \xi_{CO2_j}^{grid}. \tag{17}$$

The total battery production CO_2 impacts are calculated by multiplying the CO_2 emissions generated during the production of each battery assembly with the battery replacement frequency, which equals to the frequency of UAS flights $f_{i,j}$ for each month i divided by battery discharging cycle n_{dis}. The battery discharging cycle is the number of times the UAS battery can be discharged and charged before it needs to be replaced. The CO_2 emissions generated during the production of the airframe, denoted as $E_{CO2}^{UAV\,prod}$, is represented by

$$E_{CO2}^{UAV\,prod} = E_{CO2}^{airframe} + E_{CO2}^{battery} * \left\lceil \frac{\sum_{i,j} f_{ij}}{n_{dis}} \right\rceil. \tag{18}$$

4.3 Case Study Data Inputs

The data inputs for this study can be categorized into three dimensions: parameters specific to each city, parameters specific to Falcon L, and parameters specific to EH216.

4.3.1 Data Inputs: Cities

It is assumed that the UAS-based EMS operates 24 hours per day, 365 days per year. The UAS would be dispatched upon receiving the EMS calls. The demand of EMS cases in each city is estimated using historical data. For instance, in Helsinki, research indicates that the total number of EMS calls is 334, 207 EMS from 2013 to 2017 in Helsinki (Pirneskoski, Peräjoki, Nuutila, & Kuisma, 2016), with approximately 5% of them being Helicopter EMS (HEMS) related (Ilkka, 2022), which means helicopters are dispatched and the helicopter medical task rate is around 5%. The low, medium, and high levels of UAS EMS task rates are estimated around this percentage. In a high case scenario, the UAS-based EMS task rate is posited at 5%, commensurate with the upper bound of Air EMS deliveries observed in urban settings. Conversely, the low case UAS-based EMS task rate is estimated at 0.1%, exemplifying specialized undertakings such as the circumscribed delivery of Automated External Defibrillators (AEDs). Intermediate task rates, situated between these two polarities, encompass an array of potential UAS EMS deployment rates, offering versatility and adaptability in addressing emergent medical needs. Sensitivity analyses for the UAS EMS task rate are also conducted, with all other variables held constant.

Not all the UAS flights can be executed upon receiving the EMS calls asking for dispatching the UASs, as UAS flights are subject to weather conditions. To reflect weather influence, feasible hours for each month are estimated for each city by using the 40-year hourly-basis surface metrological data. Infeasible conditions that the UAS flights cannot be operated are ruled by predefined criteria. If any of the criteria are not met, the UAS task is deemed infeasible, otherwise the UAS task is feasible. The criteria are as follows: 1) Hourly precipitation must be less than or equal to 3 mm. 2) The temperature must be between -10 and 30 Celsius degrees (inclusive). 3) Wind speed must be less than or equal to 10 m/s. 4) There must be no risk of icing.

Figure 23 shows the distribution of infeasible probabilities for operating UAS flights across months within the targeted four cities. It is evident that in the targeted cities, the infeasible probability increases significantly during winter, thereby reducing the frequency of UAS flights for executing EMS tasks. This is particularly true for Helsinki, where the average infeasible probability in January is 64.09%, indicating that more than half the time in January, UASs cannot be dispatched successfully after receiving EMS calls.

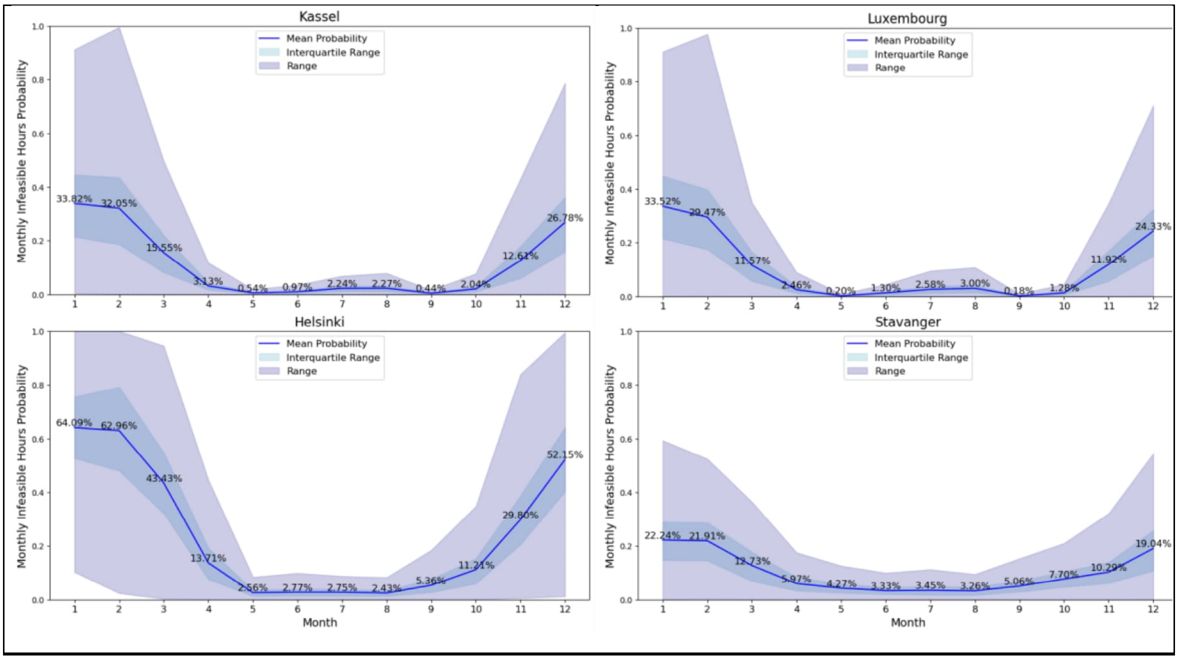


Figure 23. Monthly infeasible probabilities for operating UAS flights.

The Grid CO_2 intensity used for each city aligns with the values applied in Chapter 3. In addition to the base numbers for 2022, a constant Grid CO_2 intensity annual decrease rate is applied to each city. In the base cases, the rate is 10% per year, and sensitivity analyses for this parameter are conducted.

4.3.2 Data Inputs: Falcon L

Table 9 provided by the in-house engineer and the flight range for each task is set at 6 km since when Falcon L is loaded with 5.5 kg mass payload, its maximum flight range is 15 km with reserving battery power for safety endurance. Aircraft production CO_2 emissions (except for battery), Battery production CO_2 emissions, Vertiport construction CO_2 emissions, Outbound flight power requirement, Inbound flight power requirement are the LCA assessment results that have been validated in Chapter 3.

This study focuses solely on the emissions produced throughout the lifespan of the aircraft, effectively excluding any beyond this timeframe. It is worth noting that the operational duration of a vertiport may exceed that of the aircraft. Consequently, the emissions attributed to the construction of the vertiport, as allocated over the aircraft's entire lifetime, may represent a fraction of the total emissions generated by vertiport construction. However, the entire volume of emissions from vertiport construction is considered as a singular, non-recurring event in this study. This is grounded in the reasoning that these emissions are an unavoidable precondition for enabling flight operations.

Therefore, in this study, the full scope emissions originating from the construction phase of vertiport is taken into account, without dividing it over the aircraft's lifespan, even though the vertiport's operational life typically extends beyond that of the aircraft. It helps encapsulate the entire ecological footprint of the aviation infrastructure, accounting for all necessary prerequisites for aircraft operation.

Table 9: Parameters used for the case study conducted for Falcon L

Parameters	Functional Unit	Value
Lifetime of Falcon L	Year	4
Aircraft production CO_2 emissions (except for battery)	kg CO_2eq/aircraft	376
Battery production CO_2 emissions	kg CO_2eq/battery assembly	58
Vertiport construction CO_2 emissions	kg CO_2eq/vertiport	5,220
Outbound flight power requirement	kWh/km	0.11
Inbound flight power requirement	kWh/km	0.09
Flight range for each task	km	6

4.3.3 Data Inputs: EH216

Table 10 presented the parameters related to the EH216 used in the case study. The lifetime info is provided by the in-house engineer and the flight range for each task is set at 15 km since when EH216 is loaded with 80 kg mass passenger, its maximum flight range is 15 km with reserving battery power for safety endurance. Aircraft production CO_2 emissions (except for battery), Battery production CO_2 emissions, Vertiport construction CO_2 emissions, Outbound flight power requirement, Inbound flight power requirement are the LCA assessment results that have been validated in Chapter **Error! Reference source not found.**.

Table 10: Parameters used for the case study conducted for EH216

Parameters	Functional Unit	Value
Lifetime of Falcon L	Year	4
Aircraft production CO_2 emissions (except for battery)	kg CO_2eq/aircraft	376
Battery production CO_2 emissions	kg CO_2eq/battery assembly	58
Vertiport construction CO_2 emissions	kg CO_2eq/vertiport	5,220
Outbound flight power requirement	kWh/km	0.11
Inbound flight power requirement	kWh/km	0.09
Flight range for each task	km	6

4.4 Case Study Results and Interpretations

This sector aims to present and analyze the results of the case studies for adopting Falcon L and EH 216 in EMS scenarios. The results are visualized with different types of figures, showcasing the CO_2 Emission Pie Chart and Sensitivity Analysis Results.

4.4.1 Sensitivity Analyses and Results for Helsinki

Falcon L. A sensitivity analysis focusing on the impact of Falcon L EMS task rate as the sole variable in the context of Helsinki was simulated. The Falcon L EMS task rate refers to the proportion of EMS calls that result in the deployment of the Falcon L to address the emergency. The primary objective of this analysis is to understand the effect of varying EMS task rates on the total lifetime CO_2 emissions associated with Falcon L's operation.

The analysis reveals a positive correlation between Falcon L EMS task rate and total lifetime CO_2 emissions, see Figure 24. With the randomly sampled Falcon L EMS task ranging from 0% to 5%, the total lifetime CO_2 emissions observed throughout the simulations ranges from 10.42 to 15.57 tons CO_2eq, with the mean value 12.97 tons CO_2eq and standard deviation 1.50.

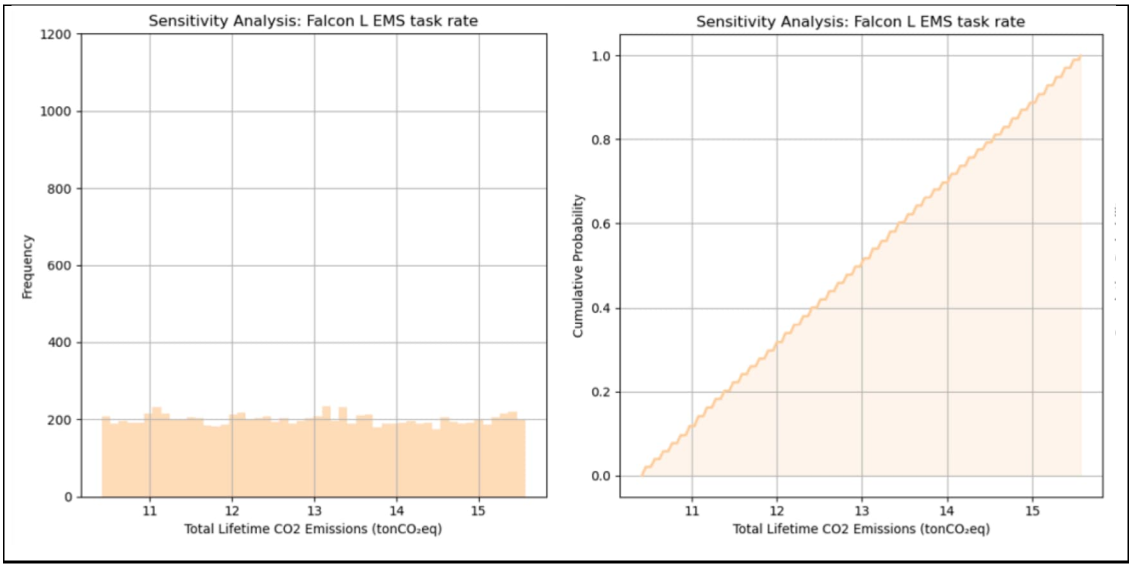


Figure 24. Analysis: Falcon L EMS task rate as the only variable (Helsinki).

Three values of the Falcon L EMS task rate are chosen for forming the high, medium, and low UAS utilization cases. The Monte Carlo method involving randomly sampling values for each variable within a specified range is applied for the sensitivity analysis for the other two variables, which are the decrease rate of grid CO_2 intensity and the battery discharging cycles. Each variable varies individually while keeping the others constant, thereby isolating the effect of each variable on the total lifetime CO_2 emissions. To be specific, the decrease rate of grid CO_2 intensity is randomly sampled from a uniform distribution within the range of 0.1 to 0.5, and the battery discharging cycles is randomly sampled from a uniform distribution within the range of 100 to 500. When one variable changes, the other variable is kept as the base-case value. The study results are depicted in Figure 25, Figure 26, Figure 27, respectively. The Pie Chart shows the simulation results with base values: the decrease rate of grid CO_2 intensity is 0.1 and the battery discharging cycles equal to 200.

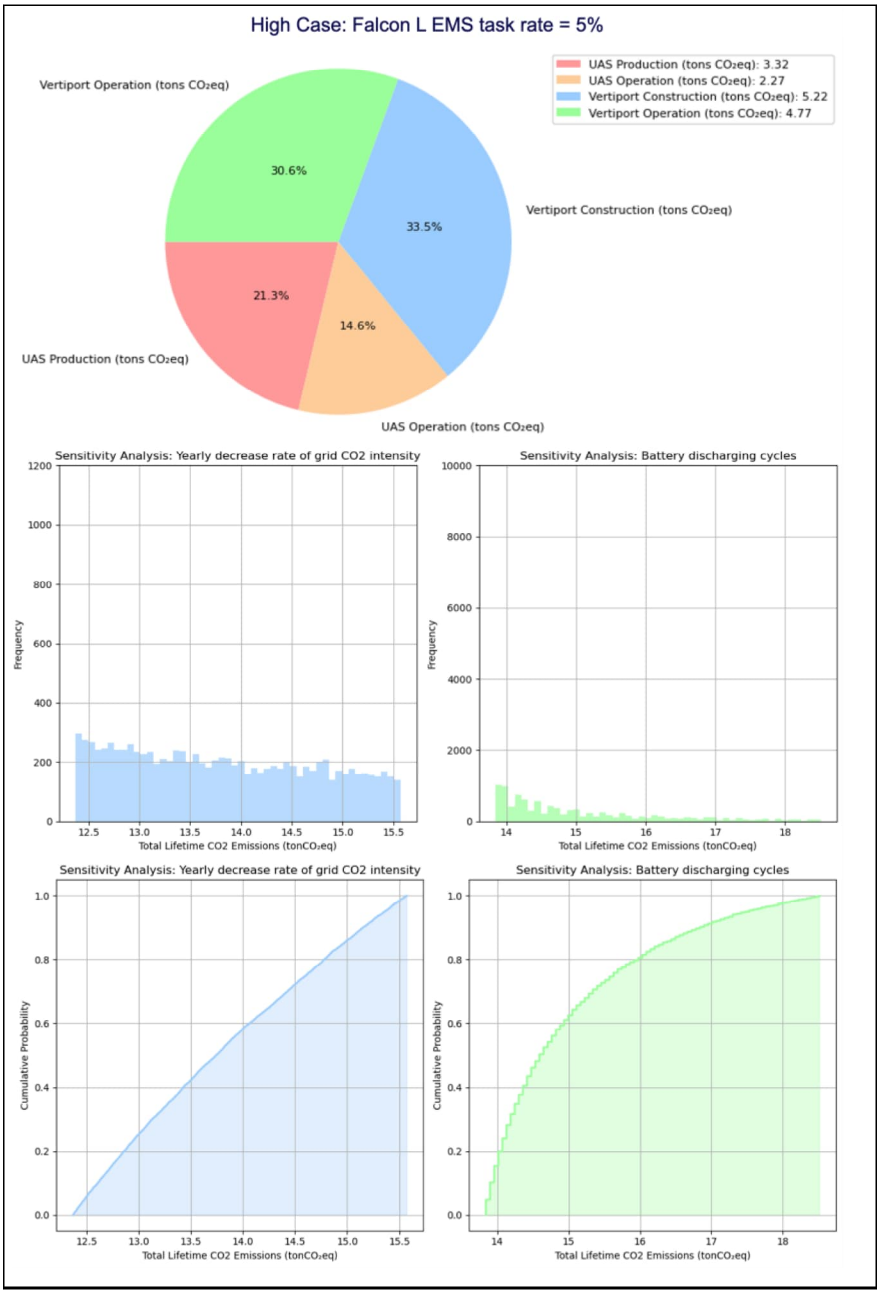


Figure 25. High case CO_2 emission pie chart and sensitivity analysis results (Falcon L deployed in its life cycle for Emergency Medical Services in Helsinki).

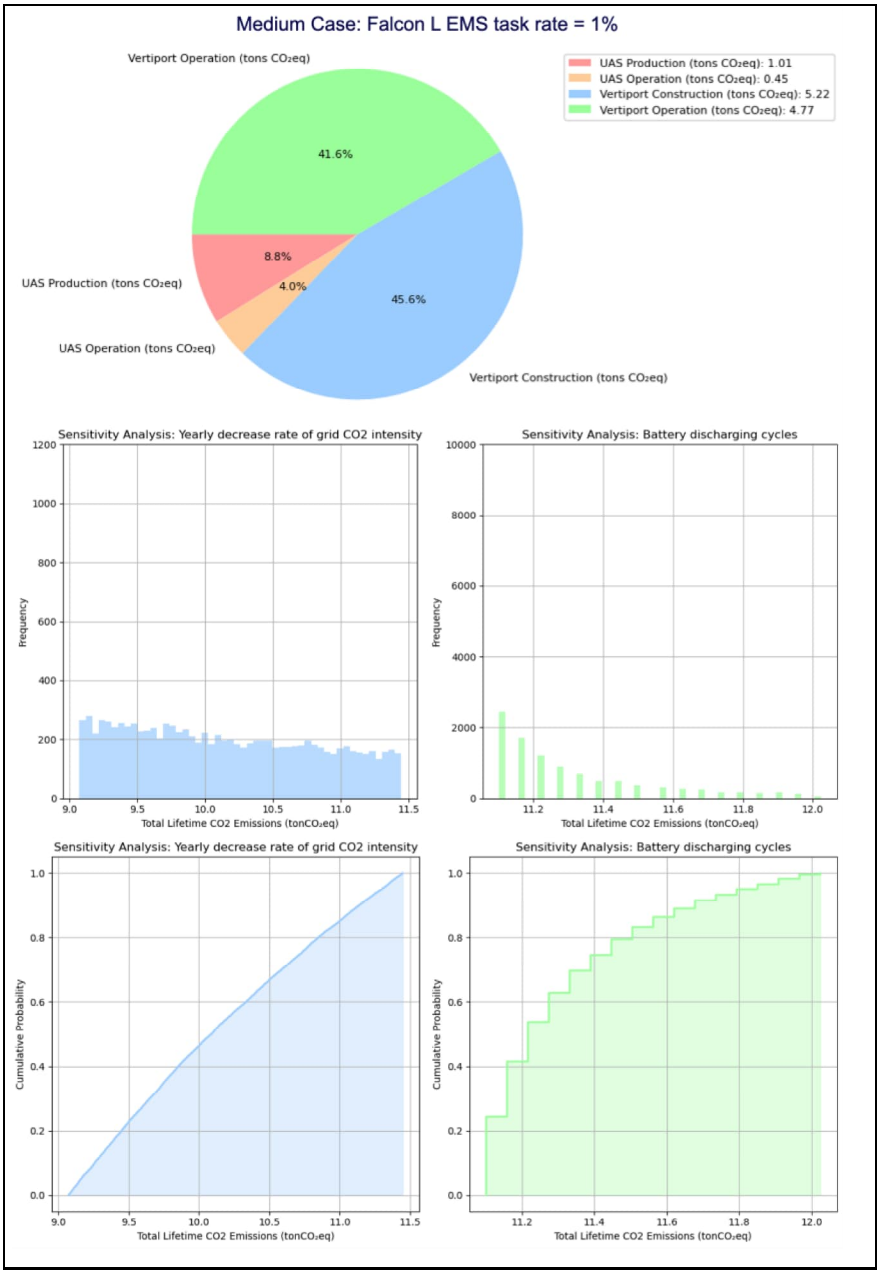


Figure 26. Medium case CO_2 emission pie chart and sensitivity analysis results (Falcon L deployed in its life cycle for Emergency Medical Services in Helsinki).

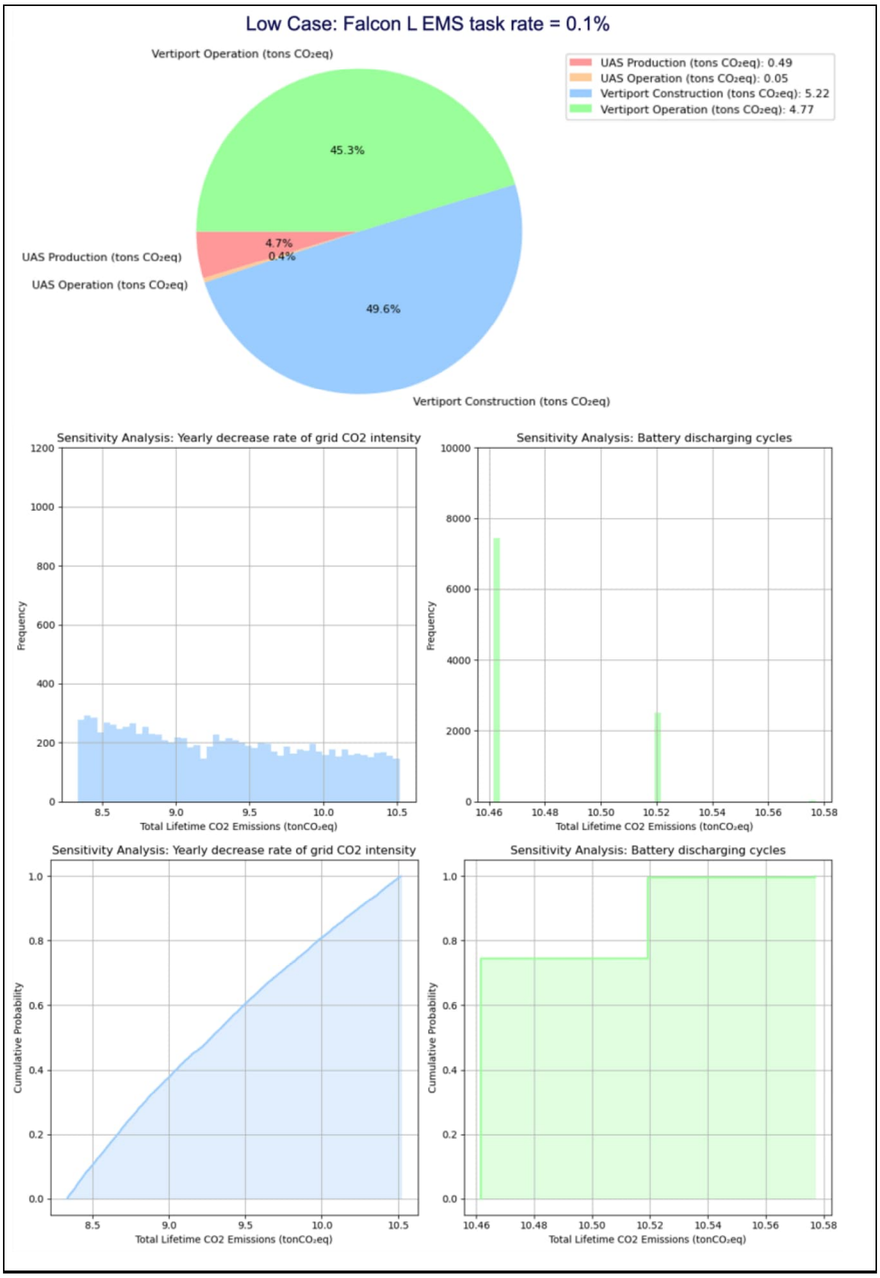


Figure 27. Low case CO_2 emission pie chart and sensitivity analysis results (Falcon L deployed in its life cycle for Emergency Medical Services in Helsinki).

In the high case simulation, the Falcon L is frequently utilized for EMS deployments within Helsinki, with an annual occurrence of approximately 2,528 instances. Consequently, the Well-to-Wheel operation emissions constitute 14.6% of the vehicle's total lifetime emissions. Under these conditions, the onboard battery assembly necessitates replacement 19 times throughout its life, resulting in the vehicle and battery production emissions contributing 21.3% to the total lifetime emissions.

Alternatively, in the medium case simulation, the Falcon L's EMS deployment frequency is reduced to roughly 506 instances per annum, leading to a decrease in Well-to-

Wheel operation emissions from 2.27 to 0.45 tons CO_2eq, which represents 4.0% of the total emissions. Concurrently, the vehicle production emissions decline from 3.32 to 1.01 tons CO_2eq, accounting for 8.8% of the total, as the battery replacement frequency is reduced to four.

In scenarios with low EMS deployment frequency, such as 50 times per year, which may be the most plausible current scenario due to the limited commercial scalability of UAM technologies, the Well-to-Wheel operation emissions are further reduced to 0.05 tons CO_2eq, comprising only 0.4% of the total emissions. Vehicle production emissions decrease to 0.49 tons CO_2eq, or 4.7% of the total, as there is no need for replacement during the Falcon L airframe's entire lifespan.

EH216. A sensitivity analysis was conducted to examine the influence of the EH216 EMS task rate as the singular variable within the Helsinki context. The EH216 EMS task rate is defined as the percentage of EMS calls that necessitate the deployment of the EH216 to address the emergency situation. Weather conditions would further influence its flight frequencies based on this EMS task rate. The primary aim of this investigation is to elucidate the ramifications of fluctuating EMS task rates on the total lifetime CO_2 emissions attributable to the operation of the EH216. As illustrated in Figure 28, the total lifetime CO_2 emissions observed throughout the simulations span 58.43 to 138.4 tons CO_2eq when the proportion of EMS calls requiring the deployment of the EH216 varies from 0% to 5%. The mean value and standard deviation of these emissions are 96.94 tons CO_2eq and 23, respectively.

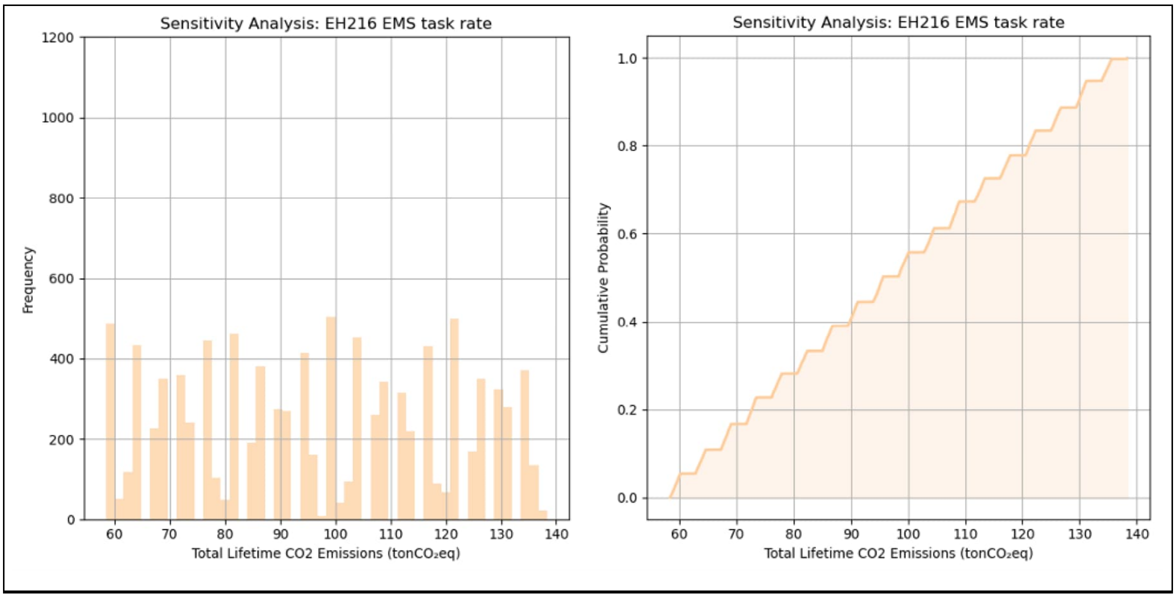


Figure 28. Sensitivity Analysis: EH216 EMS task rate as the only variable (Helsinki).

Three distinct EH216 EMS task rate values are selected to represent high, medium, and low UAS utilization scenarios. Same with dealing with the Falcon L cases, the Monte Carlo method, which entails random sampling of values for each variable within a defined range, is employed for the sensitivity analysis concerning the other two variables: the decrease rate of grid CO_2 intensity and the battery discharging cycles. By varying each variable individually and maintaining the others constant, the individual impact of each variable on the total lifetime CO_2 emissions can be isolated. Specifically, the decrease rate of grid CO_2 intensity is randomly sampled from a uniform distribution spanning 0.1 to 0.5, while the battery discharging cycles are randomly sampled from a uniform distribution ranging from 200 to 1000. When one variable is altered, the other remains at the base-case value. The research findings are illustrated in Figure 29, Figure 30, Figure 31, respectively. The pie chart presents the simulation results with base values: a decrease rate of grid CO_2 intensity of 0.1 and 700 battery discharging cycles.

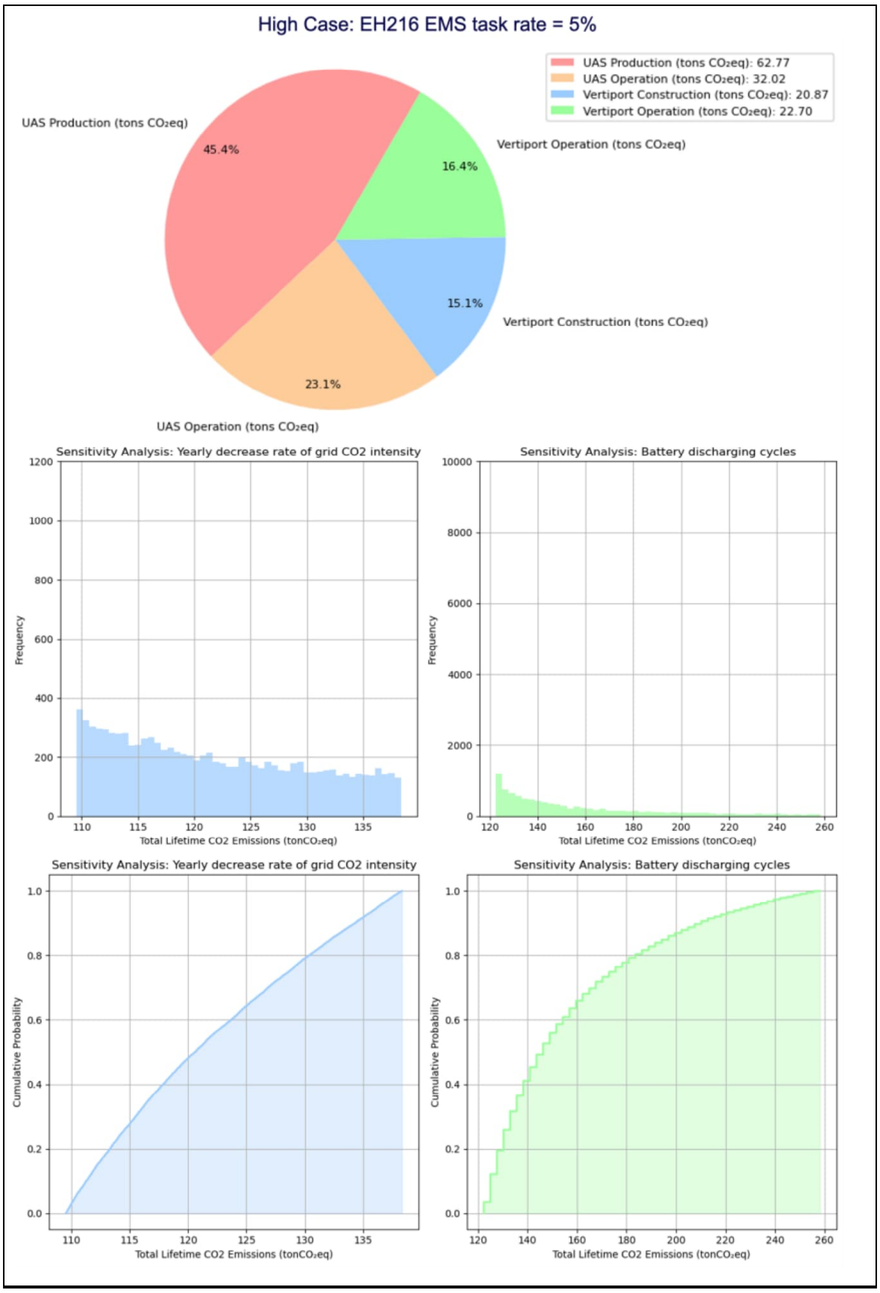


Figure 29. High case CO_2 emission pie chart and sensitivity analysis results (EH216 deployed in its life cycle for Emergency Medical Services in Helsinki).

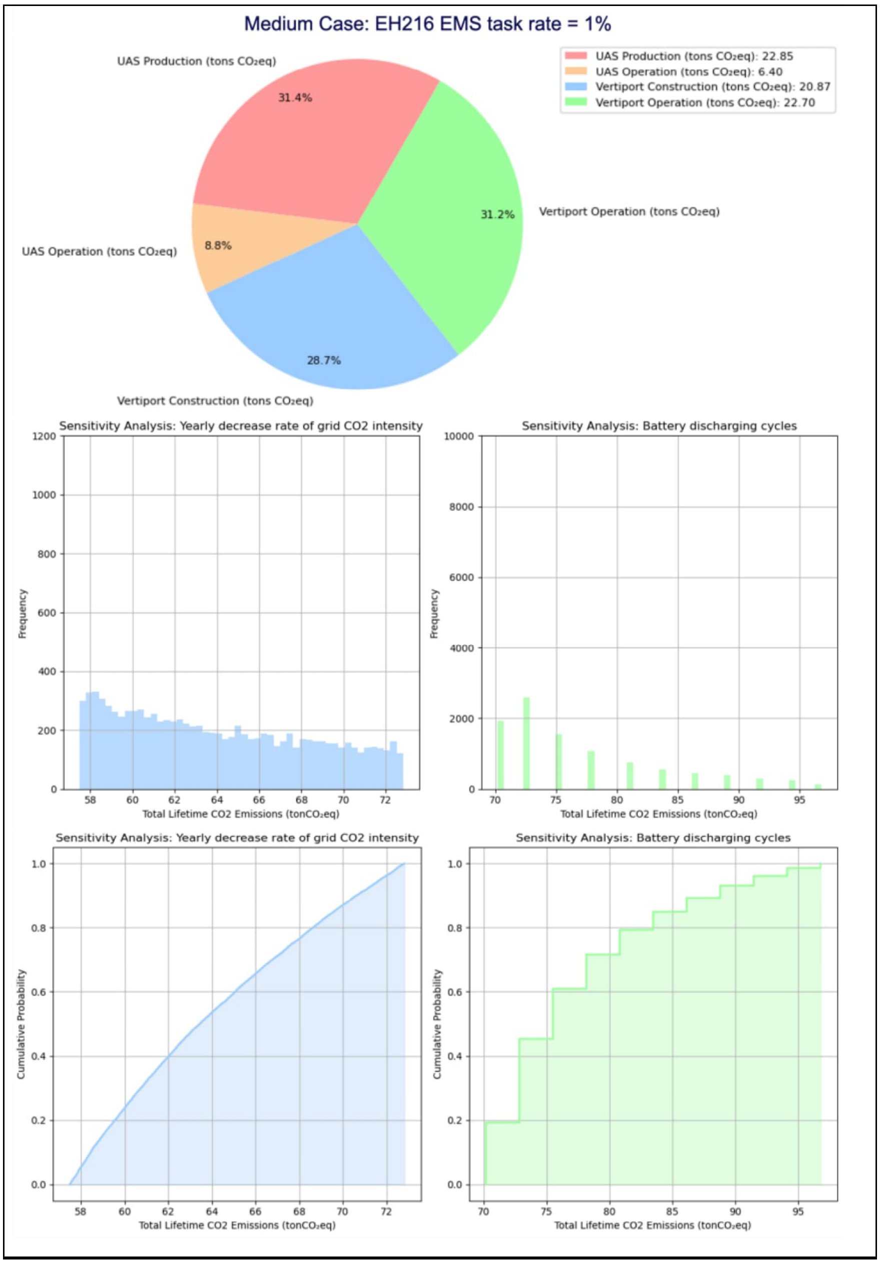


Figure 30. Medium case CO_2 emission pie chart and sensitivity analysis results (EH216 deployed in its life cycle for Emergency Medical Services in Helsinki).

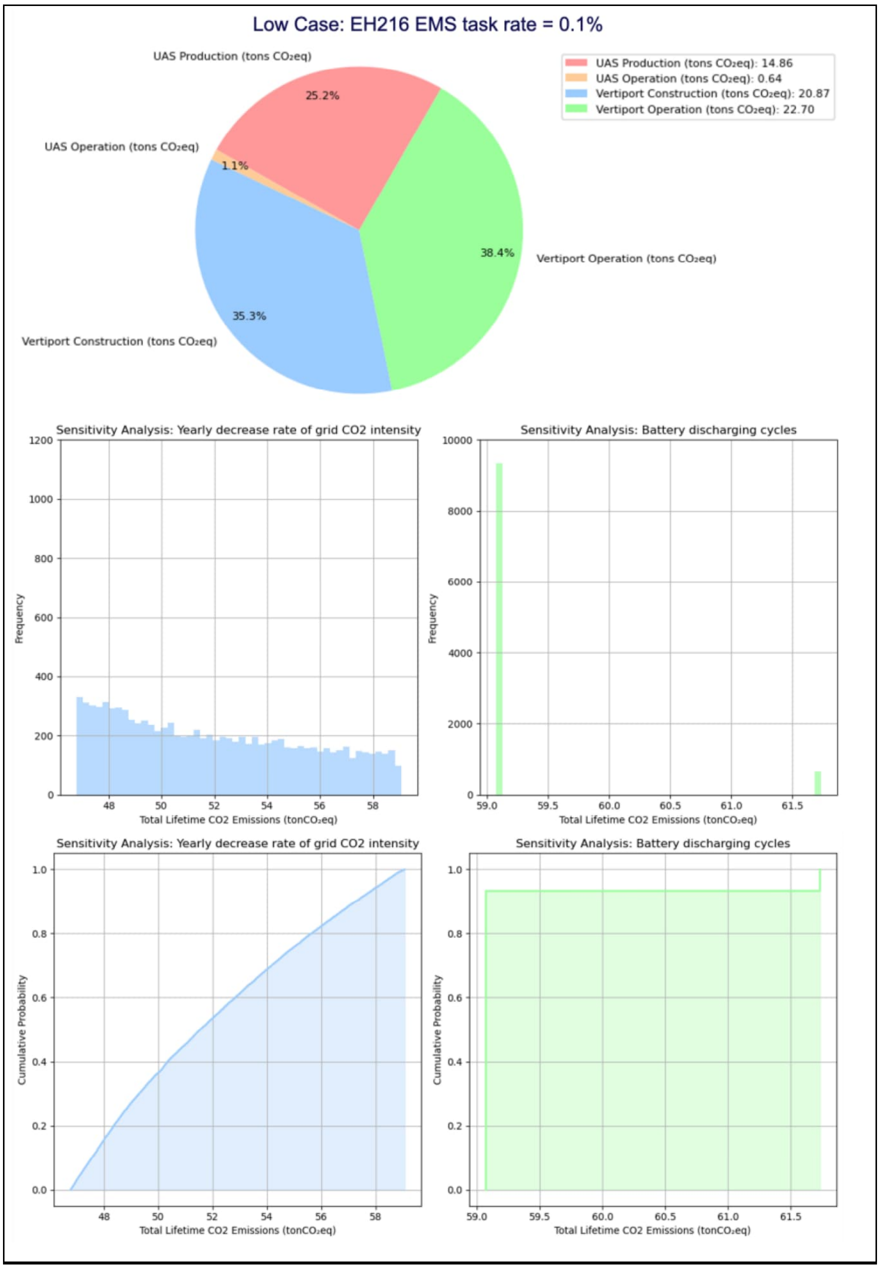


Figure 31. Low case CO_2 emission pie chart and sensitivity analysis results (EH216 deployed in its life cycle for Emergency Medical Services in Helsinki).

In the high case simulation, the EH216 is extensively employed for EMS operations within Helsinki, with an estimated annual frequency of 2,528 deployments. As a result, the Well-to-Wheel operation emissions account for 23.1% of the vehicle's total lifetime emissions, equivalent to 32.02 tons CO_2eq. Assuming optimal battery maintenance, the onboard battery assembly—comprising 16 battery packs—requires replacement 19 times during EH216's lifetime, causing vehicle and battery production emissions to contribute 45.4% to the total lifetime emissions or 62.77 tons CO_2eq.

The medium case simulation presents a reduced EH216 EMS deployment frequency of approximately 506 instances per year, leading to a decline in Well-to-Wheel operation emissions to 6.40 tons CO_2eq, representing 8.8% of the total emissions. Simultaneously, vehicle production emissions decrease to 22.85 tons CO_2eq, accounting for 28.7% of the total, as battery replacement frequency is diminished to four.

In low EMS deployment frequency scenarios, such as 50 times per year, which may currently be the most realistic scenario due to the limited commercial scalability of UAM technologies, the EH216's Well-to-Wheel operation emissions are further reduced to 0.64 tons CO_2eq, comprising a mere 1.1% of the total emissions. Vehicle production emissions drop to 14.86 tons CO_2eq, representing 25.2% of the total, as no battery replacement is needed during the entire lifespan of the EH216's main body.

Upon comparing the emission percentages and absolute values illustrated in the charts, for both Falcon L and EH216, it is apparent that the environmental impact of UAS production and operation emissions is less pronounced when UASs are deployed less frequently for EMS tasks. Conversely, the environmental impact of vertiport infrastructure gains prominence when UAS deployment frequency decreases. The absolute CO_2 emissions associated with vertiport operations remain relatively consistent across all scenarios, as the environmental impact of vertiport operations is predominantly independent of the EMS task rate. This observation can be attributed to the previous analysis, which posited that vertiport operation emissions are chiefly determined by factors such as heating, ventilation, and air conditioning (HVAC) systems and vehicle maintenance. These factors do not exhibit significant fluctuations in response to changes in UAS deployment frequency.

4.4.2 Sensitivity Analyses and Results for Other Cities

In sensitivity analyses performed for other targeted cities in this study, the data inputs remain consistent with those utilized for Helsinki, except for modifications in EMS case demands, the 2022 grid CO_2 intensity, and the probabilities of UAS flight feasibility for different cities. While these variations affect the range of total lifetime CO_2 emissions, they exhibit minimal influence on the relative contributions of each CO_2 emission category. As a result, the outcomes derived from sensitivity analyses for these additional cities corroborate the findings obtained for Helsinki. This congruence obviates the need for extensive repetition of results in this chapter, thereby emphasizing the robustness and generalizability of the established conclusions.

5 Conclusions, Limitations, and Implications

5.1 Conclusions

This study lays the groundwork for more sustainable urban air mobility solutions, by identifying the key sources that influence the carbon footprint of UAM. This study serves as a comprehensive CO_2 LCA framework for UAM, which can be readily expanded to encompass future developments and advancements in the field.

The findings reveal that emissions generated during the sourcing and production stage constitute a significant portion of Cradle-to-Grave life cycle emissions of UAM vehicles. In particular, the production of electric motors emerges as the most substantial source of emissions for multirotor drones during manufacturing. As such, efforts to enhance the production efficiency of electric motors and reduce their carbon footprint are critical for improving the overall environmental performance of UAM systems.

Additionally, the study highlights the importance of battery management in UAM operations. Frequent battery replacements not only magnify manufacturing emissions but also increase resource consumption and waste generation. Addressing these challenges requires the development of more durable and efficient batteries, as well as the implementation of advanced recycling and disposal strategies to minimize the environmental impact of battery-related processes. Also, the operational patterns of flight systems, such as frequency and duration, significantly affect battery life and, consequently, the cumulative emissions generated during the battery's lifecycle. It is imperative to evaluate the environmental impact of battery production within each specific use case, as the lifespan and associated emissions of these batteries are influenced by flight operation frequencies.

Ground infrastructure of UAM also plays a critical role in determining the overall carbon footprint of UAM systems and the sustainability levels UAM infrastructure vary across different regions. This heterogeneity can be attributed to factors such as regional weather patterns, discrepancies in energy grids, and other context-specific elements.

Climatic variations, such as temperature extremes and seasonal fluctuations, can impact the efficiency and operational capabilities of UAM systems. These meteorological factors may influence the energy consumption, range, and overall performance of aerial vehicles, as well as the demand for and resilience of UAM infrastructure. The study highlights the energy consumption with operating the ground infrastructure, particularly in relation to heating, ventilation, and air conditioning (HVAC) systems in Northern regions.

The low temperature in the winter seasons will explode the power requirements for heating UAM infrastructure, underscoring the need for careful insulation and heat management strategies in ground infrastructure components. Conversely, in regions with extremely high temperatures, the energy demand for cooling systems could escalate dramatically. This necessitates the need for efficient air conditioning and cooling mechanisms within the UAM infrastructure. Therefore, it is important to design and manage ground infrastructure to satisfy the local climate and to withstand the extremes weather conditions, optimizing energy use, and maintaining system reliability.

Moreover, regional disparities in energy grids contribute to divergent environmental footprints for UAM operations. The electricity mix, comprising renewable and non-renewable energy sources, directly affects the carbon intensity of UAM systems that rely on electric power. As such, regions with a higher proportion of clean energy sources will exhibit lower emissions and enhanced sustainability profiles.

Ground infrastructure network planning is another critical area of focus from an LCA perspective. The network planning and efficient logistics network design can help to minimize the environmental impact of UAM operations while maximizing their utility and effectiveness. It is also possible to maximize the utilization of the ground infrastructure through sharing of facilities across multiple operators, optimizing vertiport designs, or integrating UAM systems with existing transportation networks.

To conclude, sustainability measurement of UAM is faced with large uncertainties and should be measured based on specific scenarios and time horizons. The sustainability of UAM operations depends on various factors, including vehicle type and size, load capacity, and the specific transportation delivery model employed. Addressing the question of whether UAM systems are more sustainable than other modes of transportation require a nuanced and context-dependent analysis.

It is challenging to conduct a perfect comparison between UAM systems and other transportation modes due to the inherent differences in their characteristics and use cases. For instance, UAM systems may be more efficient and environmentally friendly for specific applications such as medical or disaster emergency responses, but less efficient and environmentally friendly for applications such as cargo delivery in congested urban environments, or more routine urban transportation cases where cargo bicycles or personal electric cars may prove to be more sustainable options.

One aspect that can be definitively concluded is the crucial role of cleaner grid and energy sources in enhancing the sustainability of not only UAM systems but also other transportation modes. The transition to vehicles and infrastructures powered by renewable energy sources can significantly reduce the carbon footprint and environmental impact of transportation systems across the board.

5.2 Limitations of This Study

The limitations of CO_2 LCA studies for UAM can be examined from two perspectives: data quality and methodologies improvements.

Data quality improvements. In the present study, inconsistencies in the data sources may impact the accuracy of the results. For instance, CO_2 factors utilized in the conceptual model for estimating Cradle-to-Grave CO_2 impacts of specific materials, from sourcing to end-of-life processing, are derived from different individual studies conducted in varying years and methodologies. Although this provides a preliminary estimation of production emissions, it may not accurately reflect real-world scenarios. Additionally, potential overlaps in calculations may exist, as unit-level lifecycle CO_2 factors for those materials that make up with UASs may already account for use-stage CO_2 impacts, which are considered separately in the Well-to-Wheel stage assessment this study.

Other data quality limitations include the unrepresentative nature of vertiport data inputs caused by the limited commercialization scale of UAM nowadays and the application of ground surface meteorological data that may not be entirely suitable for UAM flights. It is important to note that while traditional aviation weather platforms do provide information on various atmospheric heights, there is a significant lack of data for conditions below 150 meters above ground level. This is particularly relevant since UAS flights typically operate at around 150 meters altitude. The need for more comprehensive data on minimum icing altitude and wind conditions at these low altitudes is crucial, as complex urban weather systems, such as micro-meteorological phenomena and heat islands, are not adequately addressed by current meteorological data sources.

Methodological improvements. The current research relies on numerous arbitrary assumptions stemming from the application of conceptual models. However, real-world empirical data may yield different outcomes. For example, this study does not account for the potential impact of wind speeds and wind types (head winds or tail winds), which could significantly influence actual flight conditions and fluctuate the flight failure rates. Additionally, the study assumes that real-life flight patterns have no bearing on the evaluation results, which may not be the case in practice. UAM LCA studies are inherently complex, and as technology and market readiness evolve, different methodologies can be employed to better capture the nuances of this emerging field.

5.3 Implications of This Study

The future topics of CO_2 LCA studies of UAM stand at the threshold of immense possibilities, with far-reaching implications for both the environment and society. As the maturing of UAM industry, researchers could choose to enlarge the LCA scope, conducting Ex-Post LCA, which enables the assessment of environmental impact retrospectively. The use of tools such as EcoInvent (Wernet, et al., 2016) can help capture high-quality data flows and facilitate accurate and detailed analysis. Furthermore, the deployment of Internet of Things (IoT) technologies could enable the installation of CO_2 detectors and power meters, thus enabling the collection of real-world empirical data. This would allow for the precise tracking of CO_2 emissions during the operation of UASs and vertiports. The improved quality of data inputs would make the LCA results closer to reality so that they provide a robust and reliable basis for decision-making in the UAM sector.

With the existing framework for identifying carbon footprint categories of UASs provided by this study, the future study could be extended to the identification of strategies to reduce the CO_2 emission throughout the entire life cycle of UASs in various use cases, other than EMS.

A possible extendable topic is infrastructure, as infrastructure emission will take at least more than 50% of the total UAM system emissions even under the conservative assumptions. Researchers can investigate the potential benefits of utilizing existing facilities rather than constructing new ones, or strategically plan the distribution of different-size vertiports with various functionalities and services, reducing the need for energy-intensive construction activities and minimize the system-level environmental footprint vertiports. Furthermore, the integration of innovative materials or renewable energy sources into UAM infrastructure can be further discussed. Vertiports can be designed as self-sufficient ecosystems, producing their own energy, and reducing their reliance on conventional power sources. Smart infrastructure like building-integrated photovoltaics (BIPV) roofs, as demonstrated by a study conducted in Toronto City, Canada, offers a viable option for on-site renewable energy generation (ElSayed, Foda, & Mohamed, 2022).

Material innovation can be one other topic that could support a more sustainable life cycle of UAM. By exploring novel processing methods and material formulations, researchers can push the boundaries of what is possible in the design and manufacture of UAM components, ultimately reducing CO_2 emissions associated with their production. For example, the improvements in both the intermediate and the end-of-life processing approaches of carbon fiber composite can reduce the UAS's CO_2 emissions in the sourcing and production stage. In this study, the supplementary factor for most of the materials that make up a UAS, the factor reflecting how the end-of-life processes could affect the UAS's Cradle-to-Grave CO_2 emissions results, is 0.9-1.1 (is 0.7-1.4 for carbon fiber). However, with advanced recycling technologies or enhancing the transformation rate of reproducing those materials to new products, it is possible to significantly mitigate the CO_2 emissions resulting from the production of UASs and construction vertiports.

Battery technologies are also topics deserving future discussions within the LCA study scale. More powerful batteries have the potential to revolutionize the performance and sustainability of UAM systems in several ways, including the improvement of battery capacity and battery durability, and the development of alternative power sources. The enhanced battery capacity and the increased battery longevity not only allows for greater operational flexibility but also contributes to a more efficient use of energy resources. Other than electricity-driven powertrains, the hydrogen-driven powertrains and electrochemical capacitors also open new possibilities for the design and operation of UAM systems. By continuously exploring various powertrain options, researchers can identify the most environmentally friendly and efficient energy solutions for future UAM systems.

Last but not least, this study explored the UAM deployment EMS use cases without mapping the network of vertiports in the city and optimize the flight routes. Routing presents unique challenges for UAM systems in comparison to other modes of transportation, given the inherent limited capacity of UASs: only one-to-one delivery models can be deployed as opposed to the one-to-many transportation models employed by ground-based vehicles. Addressing these challenges in various scenarios could improve logistics efficiency and minimize the environmental impact of UAM, thereby upgrading the UAM operations to next-level maturities.

Routing topics worthy future works include sophisticated battery charging strategies, precise dispatching strategies, and integration the UAM with ground transportation systems. Identifying the most suitable times for charging and incorporating smart charging solutions can help maximize operational efficiency while minimizing energy consumption and associated emissions. Further research in this area can explore the development of intelligent algorithms for dynamic charging management. Additionally, precise dispatching such as controlling hovering times and designing flight paths also pose potential for a more sustainable UAM system. Besides, integrating UAM systems with existing ground transportation modes such as vans or electrical vehicles could be another choice. It requires that researchers, industry stakeholders, and policymakers work together, exploring the potential synergies between UAM and ground transportation systems, identifying opportunities for seamless integration and collaboration.

Bibliography

Al-Rabiaah, S., Hosny, M., & AlMuhaideb, S. (2022). An efficient greedy randomized heuristic for the maximum coverage facility location problem with drones in healthcare. *Applied Sciences, 12*(3), 1403.

Andersen, O., Hille, J., Gilpin, G., & Andrae, A. S. (2014). Life Cycle Assessment of Electronics. *SusTec 2014.* Portland, OR.

André, N. (2022). *Sustainable Design of Electric Vertical Take-Off and Landing Aircraft for Urban Air Mobility.* Doctoral dissertation, Technische Universität München.

André, N., & Hajek, M. (2019). Robust environmental life cycle assessment of electric VTOL concepts for urban air mobility. *AIAA Aviation 2019 Forum*, (p. 3473).

Ashby, M. F. (2012). *Materials and the environment: eco-informed material choice.* Elsevier.

Baldisseri, A., Siragusa, C., Seghezzi, A., Mangiaracina, R., & Tumino, A. (2022). Truck-based drone delivery system: An economic and environmental assessment. *Transportation Research Part D: Transport and Environment, 107*, 103296.

Ballo, M. (2020). *eVTOL aircraft conceptual design and optimization.* M.S. thesis, Politechnico di Milano.

Berchoff, D. (2020). *Weather-Resilient AAM Operations in Urban Environments.* Retrieved April 2023, from https://vtol.org/files/dmfile/20200422---don-berchoff---truweather---weather-solutions.pdf

Bishop, G., Styles, D., & Lens, P. N. (2021). Environmental performance comparison of bioplastics and petrochemical plastics: A review of life cycle assessment (LCA) methodological decisions. *Resources, Conservation and Recycling, 168*, 105451.

Brown, A., & Harris, W. L. (2020). Vehicle design and optimization model for urban air mobility. *Journal of Aircraft, 57*(6), 1003-1013.

Chappelle, C., Li, C., Vascik, P. D., & Hansman, R. J. (2018). Opportunities to enhance air emergency medical service scale through new vehicles and operations. *2018 Aviation Technology, Integration, and Operations Conference*, (p. 2883).

Cohen, J. K. (2019). WakeMed Health and Hospitals joins forces with UPS, FAA for drone pilot. *Modern Healthcare, 26*.

Coventry City Council. (2022). *World-first hub for flying taxis, Air-One, opens in Coventry, UK, heralding a new age of zero-emission transport*. Retrieved April 2023, from https://www.coventry.gov.uk/news/article/4232/world-first-hub-for-flying-taxis-air-one-opens-in-coventry-uk-heralding-a-new-age-of-zero-emission-transport

Das, S. (2011). Life cycle assessment of carbon fiber-reinforced polymer composites. *The International Journal of Life Cycle Assessment, 16*, 268-282.

Demir, E., Bektaş, T., & Laporte, G. (2014). A review of recent research on green road freight transportation. *European journal of operational research, 237*(3), 775-793.

Duffy, M. J., Wakayama, S. R., Hupp, R., Lacy, R., & Stauffer, M. (2017). "A Study in Reducing the Cost of Vertical Flight with Electric Propulsion. *17th AIAA Aviation Technology, Integration, and Operations Conference.*

EASA. (2019). *No: SC-VTOL-01 - Special Condition for small-category VTOL aircraft.* Retrieved April 2023, from chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.easa.europa.eu/sites/default/files/dfu/SC-VTOL-01.pdf

EASA. (2020). *MOC SC VTOL Proposed Means of Compliance with the Special Condition VTOL.* Retrieved April 2023, from https://www.easa.europa.eu/sites/default/files/dfu/proposed_moc_sc_vtol_issue_1.pdf

EASA. (2021). *MOC-2 SC-VTOL - Second Publication of Proposed Means of Compliance with the Special Condition VTOL.* Retrieved April 2023, from https://www.easa.europa.eu/en/downloads/128938/en

EASA. (2021). *Study on Societal Acceptance of Urban Air Mobility in Europe.* Cologne, Germany: EASA.

EASA. (2022). *Vertiports Prototype Technical Specifications for the Design of VFR Vertiports for Operation with Manned VTOL-Capable Aircraft Certified in the Enhanced Category (PTS-VPT-DSN).* Retrieved April 2023, from https://www.easa.europa.eu/downloads/136259/en

ElSayed, M., & Mohamed, M. (2022). The Impact of Airspace Discretization on the Energy Consumption of Autonomous Unmanned Aerial Vehicles (Drones). *Energies, 15*(14), 5074.

ElSayed, M., Foda, A., & Mohamed, M. (2022). Autonomous drone charging station planning through solar energy harnessing for zero-emission operations. *Sustainable Cities and Society, 86*, 104122.

European Climate Law. (2021, June 30). Retrieved April 2023, from EUR: https://eur-lex.europa.eu/legal-content/EN/LSU/?uri=CELEX%3A32021R1119

European Environment Agency. (2020). *CO2 Intensity of Electricity Generation*. Retrieved April 2023, from https://www.eea.europa.eu/data-and-maps/data/co2-intensity-of-electricity-generationv

Everdrone. (2022). *Everdrone success case covered by New England Journal of Medicine*. Retrieved April 2023, from https://everdrone.com/news/2022/05/20/everdrone-success-case-covered-by-new-england-journal-of-medicine/

FAA. (2022). *Memorandum subject to Engineering Brief No. 105, Vertiport Design.* Retrieved April 2023, from https://www.faa.gov/sites/faa.gov/files/2022-09/eb-105-vertiports.pdf

Figliozzi, M. A. (2017). Lifecycle modeling and assessment of unmanned aerial vehicles (Drones) CO2e emissions. *Transportation Research Part D: Transport and Environment, 57*, 251-261.

Figliozzi, M. A. (2020). Carbon emissions reductions in last mile and grocery deliveries utilizing air and ground autonomous vehicles. *Transportation Research Part D: Transport and Environment, 85*, 102443.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., & Suh, S. (2009). Recent developments in life cycle assessment. *Journal of environmental management, 91*(1), 1-21.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., & Suh, S. (2009). Recent developments in life cycle assessment. *Journal of environmental management, 91*(1), 1-21.

Gaptek. (2021). *Environmental impact of the materials used in hangar construction*. Retrieved April 2023, from https://gaptek.eu/environmental-impact-of-the-materials-used-in-hangar-construction/

Georgiev, G., Larrouturou, B., & Stjernberg, J. (2021). *AiRMOUR Deliverable 2.1 - Foresight Analysis: Urban Air Mobility Emergency Medical Services in EU cities and regions.* Retrieved April 2023, from https://drive.google.com/file/d/1rdxg-EcqRmDaOjjj9ujxBRoIURS9ozwl/view

Ghelichi, Z., Gentili, M., & Mirchandani, P. B. (2021). Logistics for a fleet of drones for medical item delivery: A case study for Louisville, KY. *Computers & Operations Research, 135*, 105443.

Goodchild, A. &. (2018). Delivery by drone: An evaluation of unmanned aerial vehicle technology in reducing CO2 emissions in the delivery service industry. *Transportation Research Part D: Transport and Environment, 61*, 58-67.

Goodrich, K. H., & Theodore, C. R. (2021). Description of the NASA urban air mobility maturity level (UML) scale. *AIAA Scitech 2021 forum*, (p. 1627).

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). *Life cycle assessment.* Cham: Springer International Publishing, .

Hellweg, S., & Milà i Canals, L. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. *Science, 344*(6188), 1109–1113.

Holden, E., Linnerud, K., & Banister, D. (2013). Sustainable passenger transport: Back to Brundtland. *Transportation Research Part A: Policy and Practice, 54*, 67-77.

Horvath, A. (2006). Environmental Assessment of Freight Transportation in the US. *The International Journal of Life Cycle Assessment, 11*(4), 229-239.

IEA. (2022). *Global Energy Review: CO2 Emissions in 2021.* Paris: IEA.

Ilkka, L. (2022). *Emergency medical services (EMS) in Finland: national data management as a path to better prehospital care.* Doctoral dissertation, Itä-Suomen yliopisto.

ISO. (2020). *ISO 14044:2006*. Retrieved April 2023, from https://www.iso.org/standard/38498.html

Johanning, A., & Scholz, D. (2014). Conceptual aircraft design based on life cycle assessment. *29th Congress of the International Council of the Aeronautical Sciences.* ICAS 2014 Proceedings.

Johnson, W., & Silva, C. (2018). Observations from exploration of vtol urban air mobility designs. *Asian/Australian Rotorcraft Forum (ARF 2018).* No. ARC-E-DAA-TN60637.

Kallitsis, E., Korre, A., & Kelsall, G. H. (2022). Life cycle assessment of recycling options for automotive Li-ion battery packs. *Journal of Cleaner Production, 371*, 133636.

Kallitsis, E., Korre, A., & Kelsall, G. H. (2022). Life cycle assessment of recycling options for automotive Li-ion battery packs. *Journal of Cleaner Production, 371*, 133636.

Kasliwal, A., Furbush, N. J., Gawron, J. H., McBride, J. R., Wallington, T. J., De Kleine, R. D., & Keoleian, G. A. (2019). Role of flying cars in sustainable mobility. *Nature communications, 10*(1), 1555.

Kirschstein, T. (2020). Comparison of energy demands of drone-based and ground-based parcel delivery services. *Transportation Research Part D: Transport and Environment, 78*, 102209.

Koiwanit, J. (2018). Analysis of environmental impacts of drone delivery on an online shopping system. *Advances in Climate Change Research, 9*(3), 201-207.

Koroma, M. S., Costa, D., Philippot, M., Cardellini, G., Hosen, M. S., Coosemans, T., & Messagie, M. (2022). Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management. *Science of the Total Environment, 831*, 154859.

Koumoutsidi, A., Pagoni, I., & Polydoropoulou, A. (2022). A New Mobility Era: Stakeholders' Insights regarding Urban Air Mobility. *Sustainability, 14*(5), 3128.

Krivohlavek, J. (2021). *AiRMOUR Deliverable 2.2 - Functional requirements for selected manned and unmanned UAM EMS scenarios.* Retrieved April 2023, from https://drive.google.com/file/d/1cQac2UwOHsgdWOTdCWUGFY2xkda-fMEw/view

Leishman, G. J. (2006). *Principles of helicopter aerodynamics.* Cambridge university press.

Liu, M., Qian, Y., Hao, H., Liu, Z., Zhao, F., Sun, X., & Geng, J. (2022). CO2 emissions from electric flying cars: Impacts from battery specific energy and grid emission factor. *eTransportation, 13*, 100189.

Maciejewski, M. (2016). Chapter 23: Dynamic Transport Services. In *The Multi-Agent Transport Simulation MATSim.* Ubiquity Press.

Maier, M. W. (1998). Architecting principles for systems-of-systems. *Systems Engineering: The Journal of the International Council on Systems Engineering, 1*(4), 267-284.

Malakoutian, M. A., Malakoutian, Y., Mostafapoor, P., & Amjadi, M. (2021). Correlation Between Energy Consumption and Building Size. *ENG Transactions, 2*, 1-6.

Masterson, V. (2022). *The European Union has cut greenhouse gas emissions in every sector - except this one*. Retrieved April 2023, from https://www.weforum.org/agenda/2022/09/eu-greenhouse-gas-emissions-transport/

Melo, S. P., Cerdas, F., Barke, A., Thies, C., Spengler, T. S., & Herrmann, C. (2020). Life Cycle Engineering of future aircraft systems: the case of eVTOL vehicles. *Procedia CIRP, 90*, 297-302.

Mohamed, N., Al-Jaroodi, J., Jawhar, I., Idries, A., & Mohammed, F. (2020). Unmanned aerial vehicles applications in future smart cities. *Technological forecasting and social change, 153*, 119293.

Mudumba, S. V. (2021). Modeling CO2 emissions from trips using urban air mobility and emerging automobile technologies. *Transportation Research Record, 2675*(9), 1224-1237.

National Highway Traffic Safety Administration. (1996). *EMS Agenda for the Future Implementation Guide.* Retrieved April 2023, from https://one.nhtsa.gov/people/injury/ems/agenda/execsum.html

Nordelöf, A., Grunditz, E., Lundmark, S., Tillman, A. M., Alatalo, M., & Thiringer, T. (2019). Life cycle assessment of permanent magnet electric traction motors. *Transportation Research Part D: Transport and Environment, 67*, 263-274.

Park, J., Kim, S., & Suh, K. (2018). A comparative analysis of the environmental benefits of drone-based delivery services in urban and rural areas. *Sustainability, 10*(3), 888.

Patel, S. R., Gunady, N. I., Rao, A. K., Wright, E. C., & DeLaurentis, D. (2022). Modeling Energy Infrastructure of Future Electric Urban Air Mobility Operations. *2022 17th Annual System of Systems Engineering Conference (SOSE)* (pp. 382-387). IEEE.

Pirneskoski, J., Peräjoki, K., Nuutila, M., & Kuisma, M. (2016). Urgent EMS managed out-of-hospital delivery dispatches in Helsinki. Scandinavian Journal of Trauma,. *Resuscitation and Emergency Medicine, 24*(1), 1-6.

Ploetner, K. O., Al Haddad, C., Antoniou, C., Frank, F., Fu, M., Kabel, S., & Zhang, Q. (2020). Long-term application potential of urban air mobility complementing public transport: an upper Bavaria example. *CEAS Aeronautical Journal, 11*, 991-1007.

Pollock, A. 2. (2013). Ambulance services in London and Great Britain from 1860 until today: a glimpse of history gleaned mainly from the pages of contemporary journals. *Emergency Medicine Journal, 30*(3), 218-222.

Prakasha, P. S., Naeem, N., Ratei, P., & Nagel, B. (2022). Aircraft architecture and fleet assessment framework for urban air mobility using a system of systems approach. *Aerospace Science and Technology, 125*, 107072.

Reiche, C., Brody, F., McGillen, C., Siegel, J., & Cohen, A. (2018). *An Assessment of the Potential Weather Barriers of Urban Air Mobility (UAM).* Retrieved from https://escholarship.org/uc/item/2pc8b4wt

Ribeiro, J. S., & de Oliveira Gomes, J. (2015). Proposed framework for end-of-life aircraft recycling. *26*, 311-316.

Rodrigues, T. A., Patrikar, J., Oliveira, N. L., Matthews, H. S., Scherer, S., & Samaras, C. (2022). Drone flight data reveal energy and greenhouse gas emissions savings for very small package delivery. *Patterns, 3*(8), 100569.

Rothfeld, R., Balac, M., Vetrella, A. R., & Schmid, B. (2019). Demand estimation for aerial vehicles in urban settings. *IEEE Intelligent Transportation Systems Magazine, 11*(3), 105-116.

Schweiger, K., & Preis, L. (2022). Urban air mobility: systematic review of scientific publications and regulations for vertiport design and operations. *Drones, 6*(7), 179.

Steiner, M. (2019). Urban air mobility: Opportunities for the weather community. *Bulletin of the American Meteorological Society, 100*(11), 2131-2133.

Steiner, M. (2020). *Weather Challenges for Advanced Aerial Mobility in Urban Environments.* Retrieved April 2023, from https://vtol.org/files/dmfile/20200422---matthias-steiner---ncar---weather-challenges---no-animations2.pdf

Stolaroff, J. K., Samaras, C., O'Neill, E. R., Lubers, A., Mitchell, A. S., & Ceperley, D. (2018). Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery. *Nature communications, 9*(1), 409.

Uber Elevate. (2016). *Fast-Forwarding to a Future of On-Demand Urban Air Transportation*. Retrieved April 2023, from https://evtol.news/__media/PDFs/UberElevateWhitePaperOct2016.pdf

United Nations Environment Programme. (2022). *Emissions Gap Report 2022: The Closing Window Climate crisis calls for rapid transformation of societies*. Retrieved from https://www.unep.org/emissions-gap-report-2022

UPS. (2016). *UPS 2015 Corporate Sustainability Report.* Atlanta, Georgia, USA: United Parcel Service.

Vajna, S. (Ed.). (2020). *Integrated Design Engineering: Interdisciplinary and Holistic Product Development.* Springer Nature.

van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G. J., & Tukker, A. (2020). A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production, 259, 120904., 259*, 120904.

Vandepaer, L., Cloutier, J., & Amor, B. (2017). Environmental impacts of Lithium Metal Polymer and Lithium-ion stationary batteries. *Renewable and Sustainable Energy Reviews, 78*, 46-60.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment, 21*, 1218-1230.

Wulf, C., Zapp, P., Schreiber, A., Marx, J., & Schlör, H. (2017). Lessons learned from a life cycle sustainability assessment of rare earth permanent magnets. *Journal of industrial ecology, 21*(6), 1578-1590.

Yun, C. Y., Park, I. K., Lee, H. Y., Jung, J. S., Hwang, I. S., & Kim, S. J. (2007). Design of a new unmanned aerial vehicle cyclocopter. *Journal of the American Helicopter Society, 52*(1), 24-35.

Zhang, J. (2021). *Economic and Environmental Impacts of Drone Delivery.* Doctoral dissertation, University of Missouri-Saint Louis.

Zhao, P., Post, J., Wu, Z., Du, W., & Zhang, Y. (2022). Environmental impact analysis of on-demand urban air mobility: A case study of the Tampa Bay Area. *Transportation Research Part D: Transport and Environment, 110*(103438).