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A Comparative Review of Air Drones (UAVs) and Delivery Bots (SUGVs) for Automated Last Mile Home Delivery

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Abstract: *Background*: UAVs (Unmanned Aerial Vehicles) and SUGVs (Sidewalk Unmanned Ground Vehicles) are two prominent options to revolutionize last mile home delivery. However, there is no literature yet addressing a comprehensive assessment of them. To bridge this research gap, this paper aimed to compare UAVs to SUGVs in the context of urban parcel delivery from a practical, conceptual, technological, commercial, and environmental perspective. *Methodology*: Based on structured literature and web research, this paper provided a comparative status quo review of these two delivery concepts. We introduced a parameter-based cost calculus model to estimate the costs per shipment for each technology. To detect the key cost drivers, we applied a one-way sensitivity analysis, as well as a "full factorial design of experiment" approach. *Results*: These key cost drivers for both operations are the "number of vehicles per operator" and the "average beeline service radius". From today's commercial point of view, our model indicated better profitability of SUGVs. However, technical and regulatory developments may render different results in the future. As SUGVs emit significantly less noise than UAVs, we assume that SUGVs have an additional advantage for usage in autonomous urban last mile delivery from a resident's perspective. *Conclusions*: Both key cost drivers will significantly influence the commercial viability of unmanned home delivery services. Safety and security aspects will determine regulatory rules on "number of vehicles per operator". To increase the "average beeline service radius", UAVs could profit from mothership delivery concepts while SUGV delivery may co-use existing public transport infrastructure.

Keywords: automated vehicles; cost analysis; delivery bots; drones; last mile delivery; noise; sidewalk unmanned ground vehicles; SUGV; unmanned aerial vehicles; UAV

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1. Introduction

Urban last mile delivery, i.e., the transport of goods from local hubs to private customers in urban areas, is facing increasing challenges such as growing volumes, time pressure, cost, aging workforce, and sustainability [1]. Automated delivery options have large potential to reduce driver shortage [2] and traffic volume [3]. There are two competing drone delivery options which either employ Unmanned Aerial Vehicles (UAVs) or Sidewalk Unmanned Ground Vehicles (SUGVs). For simplicity, the word "drone" is used in the following text to represent both UAVs (air drones) and SUGVs (ground drones).

Both drone technologies emerge increasingly in field tests and commercial operations, as, e.g., Amazon's UAV prime air test in the US [4], Domino's UAV pizza delivery in New Zealand [5], Zipline's UAV medical delivery in Africa [6], and Starship's SUGV use for food delivery in the UK [7] and in the US [8]. Logistics operators, e-commerce sales organizations, and drone manufacturers are striving to achieve technological improvements and regulatory simplifications, while an increasing amount of academic research focuses on optimizing operational models for drone delivery based on different drone use concepts.

However, so far we found no literature addressing a comprehensive assessment of both drone delivery concepts. Therefore, this paper provided an overview of the current status of drone delivery from a practical implementation perspective and a scientific research perspective and provides a methodology to commercially compare the costs of air drone (UAV) and delivery bot (SUGV) operations.

1.1. Research Questions

For logistics service providers, it is of significance to have a comprehensive understanding of these two options for last mile delivery to make economically and ecologically robust decisions. This paper aimed to compare UAVs to SUGVs in the context of urban parcel delivery from a practical, theoretical, technological, commercial, and environmental perspective by answering the following research questions:

1. What is the status quo of these two technologies' applications in urban last mile delivery from a practice use perspective? (Section 2);
2. What are the emerging delivery concepts of both technologies in the research literature? (Section 3);
3. What are the key technical characteristics of both technologies? (Section 4);
4. Which technology is more beneficial for commercial players? (Section 5);
5. Which technology is more beneficial for the environment? (Section 6).

Thus, our research neither focuses on further aspects of drone usage in last mile home-delivery such as, e.g., "societal impacts", "safety and security", "communication", "societal impacts", "legal regulation", and "formal OR-problem modelling", nor does it include aspects on drone usage outside last mile home-delivery, such as, e.g., "military drone usage".

1.2. Methodological Approach

In Sections 2–4, we performed structured literature, and web research to summarize the status quo of (pre-)commercial use cases and (pre-)commercial drone use concepts. The keywords used for literature and web search were "delivery robot", "drone delivery", and "autonomous last mile logistics".

In Section 5, a cost calculus template considering investments and operating cost components is introduced to assess the cost per shipment of drone delivery. With the aid of interviews with one UAV and one SUGV manufacturer, we obtained the cost parameters needed to perform an exemplary cost calculation. To identify the impact of different cost parameters on these results, we employed a "ceteris paribus" (also termed "one-way" sensitivity analysis) based on the exemplary cost calculation scheme combined with a "full factorial design of experiments approach" considering a plausible variation range of sensitive cost parameters.

In Section 6, some selected environmental aspects are discussed, and the need for further research is indicated.

2. Intermediate Use Case Overview

To depict the status quo from a practical perspective, several non-exhaustive use cases were selected covering drone deliveries of food, medical supplies, and parcels in the Asian, European, and American markets. They were investigated and sorted according to participants' roles, product types, and operation status. As a result, the general evolution of drone delivery is visualized in the following timeline graphic (Figure 1).

2.1. UAV

Because of the independence from road infrastructures and the possible maximal flight speed, UAVs are typically used to transport emergency medical supplies such as blood, vaccines, medical samples, or equipment to remote or otherwise inaccessible regions. Besides, UAVs have increasingly been adopted in grocery and parcel delivery, especially during the current COVID-19 pandemic. The selected use cases are introduced below in ascending alphabetic and chronological order. We use the notation [<company>, <country

code>, <year>] to describe specific drone use cases; the notation (<author>, <year>) denotes the relevant literature source.

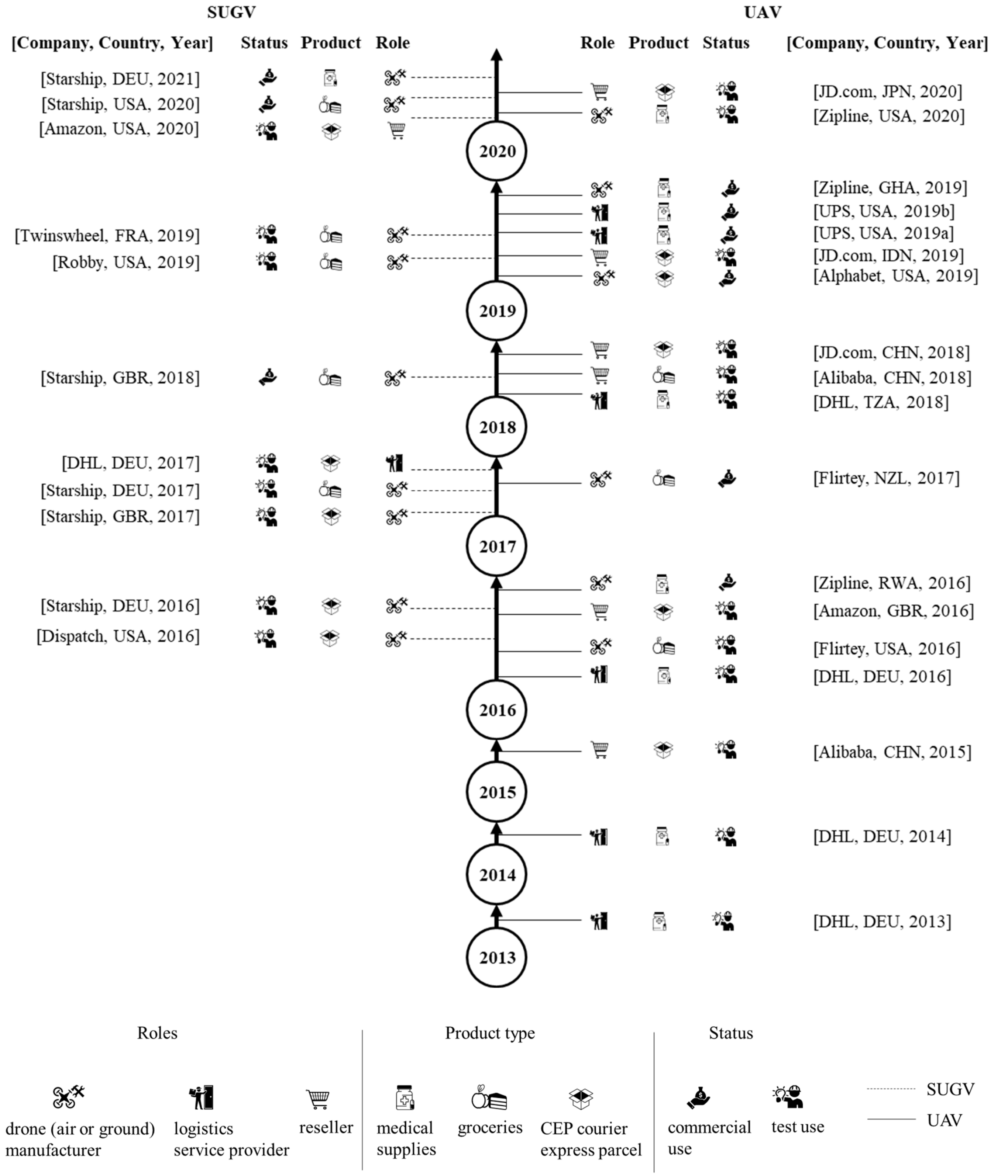

Figure 1. Overview of the selected drone delivery use cases.

Alibaba (CHN, 2015) started testing its UAV delivery in 2015 for three days from selected distribution centers to customers within a one-hour flight [9]. In 2018, Alibaba (CHN, 2018) used UAVs in a pilot program to deliver food and parcels in the Shanghai Jinshan Industrial Zone before a ground courier picked them up and delivered them to end customers [10].

Alphabet (USA, 2019) launched the first US commercial service of delivering on-demand groceries to the general public in Virginia and it saw a significantly increasing demand during the COVID-19 pandemic since people preferred to adhere to distance policies [11]. In the same month, Alphabet's Wing Aviation gained the approval of the Federal Aviation Administration (FAA) Standard Part 135 air carrier certificate in October 2019. Alphabet also runs UAV operations in Finland and Australia.

Amazon (USA, 2013), an e-commerce service provider, announced its ambition to deliver regular packages within 30 min with UAVs early in 2013. However, since the planned flight is over people, Amazon (GBR, 2016) did not yet offer their Prime Air service for commercial operations except for several tests in the UK, where Amazon's delivery idea is regarded with less skepticism than in the US [12]. Amazon Prime Air earned the FAA Standard Part 135 air carrier certificate in 2020, which gave Amazon the ability to carry property on small UAVs "beyond the visual line of sight" of operators [13].

DHL (DEU, 2013) started its test in 2013 in Bonn by delivering medical supplies over the river for one week. In the last 3 months of 2014, DHL (DEU, 2014) tested its first-generation parcelcopter from mainland Norddeich to the island of Juist in Germany. The goods were dropped off at the landing site on the coastline and were picked up by a DHL courier who transported them to the recipients. In 2016, DHL (DEU, 2016) conducted a three-month trial in the Alps of a specially developed parcelcopter and a matching sky-port for vertical launching and landing of the third-generation parcelcopter [14]. The parcelcopter was delivering cargo such as medicines and sports equipment in that trial. In 2018, DHL (TZA, 2018) achieved success with a fourth-generation parcelcopter after a six-month test in the "delivery future" pilot project, delivering medical supplies from the mainland to Ukerewe island in Lake Victoria, East Africa [15].

Flirtey (USA, 2015), a Nevada-based UAV manufacturer, received the first approval from the FAA in July 2015 for a one-weekend test delivering medical supplies from a regional airport to a health clinic in rural southwest Virginia, US [16]. In the weekends from July to the end of 2016, Flirtey (USA, 2016) completed 77 UAV deliveries with Seven-Eleven for preselected customers in Reno, Nevada, US [17]. In 2017, Flirtey (NZL, 2017) started the first commercial pizza delivery with DRU (i.e., Domino's Robotic Unit) in New Zealand by cooperating with Domino's [18].

JD.com (CHN, 2018), another Chinese e-commerce retailer, was the first company in China to obtain a provincial license for UAV operation in 2018 and has tested its UAVs in seven Chinese provinces [19]. Besides, JD.com completed trial delivery in Indonesia (JD.com, IDN, 2019) [20] and in Japan's mountainous region (JD.com, JPN, 2020) in cooperation with the company Rakuten [21].

UPS (USA, 2017), a global logistics service provider, has also actively participated in medical UAV deliveries. In 2017, UPS successfully tested launching UAVs from the top of a package delivery van produced by Workhorse [22]. In March 2019, together with Matternet's M2, UPS (USA, 2019a) initiated an ongoing revenue-generating UAV delivery service at WakeMed's flagship hospital and campus in Raleigh, N.C. Medical samples were delivered from a doctor's office to a central testing lab on campus under the FAA's Part 107 rules which allow flights "in line of sight" only [23]. In early May 2019, UPS (USA, 2019b) used Matternet's M2 to deliver prescription medicines from a Florida CVS (Consumer Value Stores) pharmacy for the largest retirement community in the USA [24], still under the FAA's Part 107 rules. In this case, UPS ground couriers picked up the dropped shipments and handed them over to the ground destination at the end. In June 2019, UPS found a subsidiary, Flight Forward, approved by the FAA Standard Part 135 air carrier certificate in September 2019.

Zipline (RWA, 2016), a California-based UAV manufacturer founded in 2014, provided the first national live UAV operation in 2016 for the East African country of Rwanda where UAV legislation was applauded [25]. In the distribution centers of Zipline in central regions of Rwanda, UAVs were loaded with products that were directly stored in the same distribution center, or with cross-dock products [26]. In 2019, Zipline (GHA, 2019) expanded live UAV operations to Ghana [27]. Given FAA approval for flights over two routes in the US in 2020, Zipline (USA, 2020) delivered medical supplies and personal protective equipment for use against the COVID-19 pandemic along the routes to a Novant Health Medical Center in Charlotte, North Carolina [28].

2.2. SUGV

SUGVs are primarily used to deliver groceries. Besides, they have also been tested to carry heavy goods, e.g., for senior shoppers or postmen. Selected cases are introduced below in ascending alphabetical and chronological order.

Amazon (USA, 2020) has rolled out its SUGV "scout" in four cities so far for field tests in the US to deliver packages to selected customers. Because the delivery robots were still in testing, the robot was initially accompanied by a human [29].

DHL (DEU, 2017) tested their SUGV "post-bot" in Bad Hersfeld, Germany in a collaborative mode to support postmen by carrying heavy items on a SUGV automatically following the postmen [30].

Dispatch (USA, 2016) used their SUGV "Carry" for food and laundry delivery in a test [31]. It is characterized by a rather big capacity with four respective compartments and can hold goods up to 50 kg altogether. This allows customers to pick up their packages from an independent compartment so that security with regard to theft is granted. At Menlo College and CSU Monterey Bay, the SUGV was used in a test to deliver letters and packages to students [32].

Robby (USA, 2019) tested their SUGV "Robby" in 2019 with Pepsico at the University of the Pacific in Stockton, California to deliver snacks, drinks, breads, and other food to students on campus [33].

Starship Technologies (EST/GER, 2016), a US/Estonian startup founded in 2014, is one of the leaders in the field of SUGV delivery. Starship and Mercedes-Benz introduced the so-called mothership concept in September 2016. An early prototype emerging from the cooperation was the Mercedes-Benz Sprinter, acting as a mobile loading and transport hub for eight starship SUGVs [34]. Starship SUGVs (Starship, DEU, 2016) tested parcel delivery for Hermes in parts of Hamburg from June 2016 to March 2017 [35]. In 2017, Hermes tested Starship's SUGVs (Starship, GBR, 2017) to collect returned goods from selected customers as mobile pick-up points in London [35]. In the same year, Starship (DEU, 2017) joined a pilot program with Domino's to deliver pizzas in one district of Hamburg [36]. All these tests were accompanied by a human. The first commercial service (Starship, GBR, 2018) without any human accompanying the drone was launched in April 2018 in Milton Keynes, UK by cooperating with local restaurants and grocery stores to deliver food and groceries to almost 200,000 residents in the town [37]. Later on, Starship (USA, 2020) expanded a similar service to 10 university campuses and 3 cities in the US as of September 2020 [37]. Recently, Starship (DEU, 2021) SUGVs were running in Hamburg to deliver COVID-19 test sets to residents who paid for this option [38].

Twinswheel (FRA 2019), a French-based startup, produces special SUGVs with a large payload to free the hands of users from heavy goods. Twinswheel (FRA, 2019) tested their "follow me" SUGVs in a superstore in Paris [39]. The SUGV followed shoppers (e.g., elderly or disabled individuals) and transported their shopping goods of up to 40 kg to their cars or homes. Working with French post, the SUGVs are planned to follow mail carriers during their shifts firstly in the collaborative mode, and, step by step, the robots are expected to deliver all parcels in a fully autonomous mode [40].

3. Drone Delivery Concept Overview

This chapter investigates by which concepts UAVs and SUGVs can be employed for last mile delivery and aims to provide an overview of the potential application concepts from a theoretical perspective.

As depicted in Figure 2, we suggest categorizing the concepts into three uniform categories:

- direct delivery (drones deliver directly from depot to customer);
- indirect delivery (i.e., two-tier execution of last mile via local mini-hubs or cross-docking points);
- mothership delivery (i.e., drones are partly carried by other means of transport toward their destination).

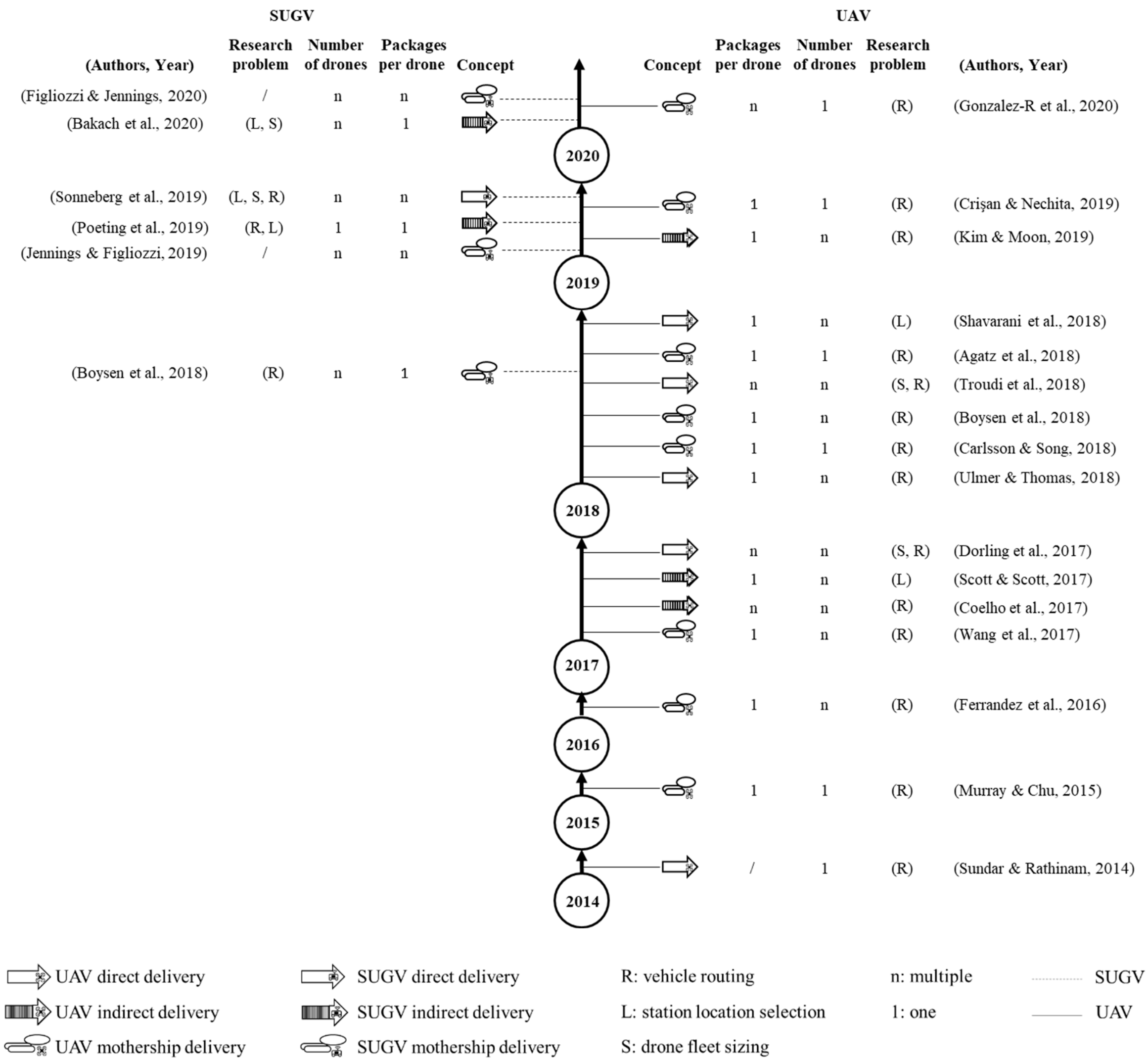

Figure 2. Overview of the selected literature on different drone delivery types.

In all three categories, goods are transported from origins to destinations, where origins are defined as depots (or warehouses) and destinations are defined as general drop points including parcel lockers, pick-up shops, and homes of end customers. (Without a special declaration, the term "customer/customers" generically describes "destination drop points" in the following text). An overview of all reviewed literature in this chapter is presented in Figure 2.

We are aware that other authors suggest different categorization schemes. Recent research [41] on classifying the frameworks of UAV-based logistics models, e.g., suggest categorizing UAV concepts into four main groups: pure-play drone-based models, unsynchronized multi-modal models, synchronized multi-modal models, and resupply multi-modal models. By considering further factors such as the number of depots, the number and capacity of UAVs, and the number and capacity of supporting vehicles, these basic four groups can be classified into extensive subcategories.

However, we decided to use our more simplified classification scheme that uniformly includes both air and ground drone concepts to highlight the basic conceptual differences and to not become side-tracked by a more complex classification scheme.

3.1. Direct Drone Delivery

In this concept, UAVs and SUGVs are used alone without collaborating with any other vehicles to deliver shipments directly from the central/local warehouse to drop points and return vice versa after the mission, as shown in Figure 3. Literature related to this concept is referred to below in ascending order of the publication year.

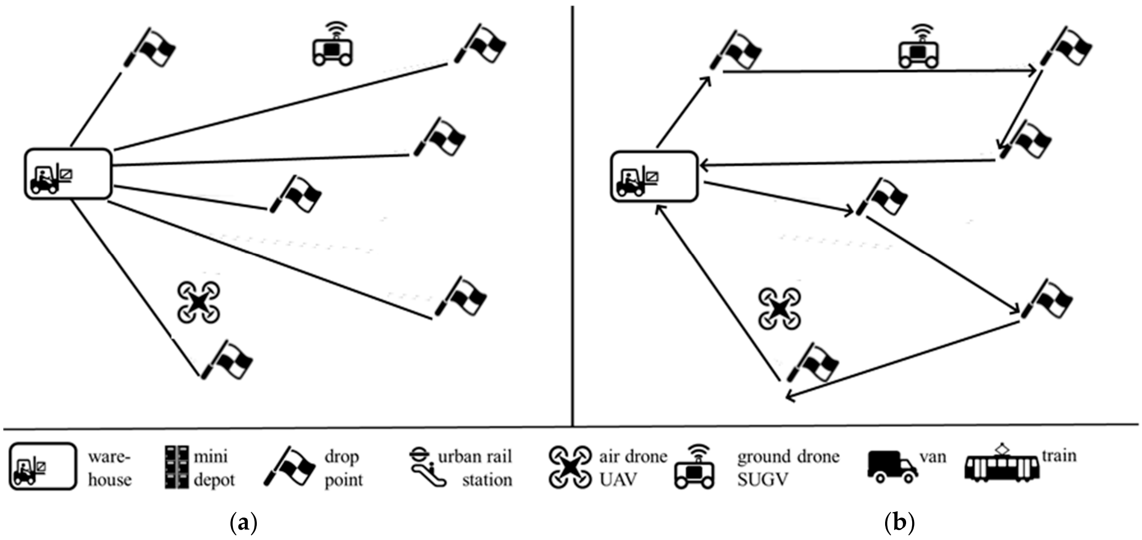

Figure 3. Delivery concept of direct drone delivery: (**a**) single stop, (**b**) multi-stop.

3.1.1. UAV

Ref. [42] analyzed a single-UAV routing problem in the configuration characterized by a small UAV departing from one depot possibly stopping at several other depots for recharging before it reaches the end location. The objective was to identify the minimum-cost path that reached all target locations considering the limited battery range of UAVs. Since the drone analyzed in this paper was not employed in a delivery context, the payload capacity of the drone was not taken into consideration. (Since there are no other vehicles involved, we associate this process with the concept of direct drone delivery).

Ref. [43] developed mixed-integer linear programs to optimize the fleet size and routes of UAVs with the objective to minimize delivery cost and delivery time, respectively. The network was composed of one depot and multiple demand locations. Within the battery range and UAV capacity, one UAV could serve multiple demand locations in a flight route without flying back to the depot and one UAV could perform more than one route in a day. They considered two types of UAVs: one with a built-in battery and another with a swappable battery. The energy consumption of a multi-rotor UAV was assumed as a linear function of its battery capacity and payload weight. As a result, a limited number of UAVs built with swappable batteries plus a set of extra batteries of different capacities were recommended for maximal time and cost savings.

Ref. [44] analyzed a hierarchical network of direct UAV deliveries where UAVs departed from launch stations (first level), and if needed via recharge stations (second level), to end customers. Each UAV was loaded with only one shipment at the launch station. Launch stations were central warehouses that stored goods and UAVs while recharge stations provided only charging infrastructures. A distance-constrained mobile hierarchical facility location model was used to find the optimal number and locations of launch and recharge stations so that the total costs of the system were minimized. System costs included set-up costs for launch and recharge stations, UAV procurement, and UAV usage costs. This model was applied to the case of Amazon Prime Air deliveries in San Francisco. It aimed to provide related business stakeholders with information such as UAV fleet size planning, investment composition, and profit evaluation.

Ref. [45] formulated a capacitated vehicle routing problem with time windows to optimize the size of the UAV fleet and the number of required batteries. Each UAV was re-equipped with a fully charged battery between two missions and a UAV was able to deliver multiple parcels in a flight under the battery's energy constraint.

Ref. [46] proposed the use of UAVs in parallel to conventional trucks to deliver packages directly from the central warehouse to end customers on the same day. UAVs and trucks operated independently. A UAV flight served only one customer at a time and it returned afterward to the depot for recharging and reloading for the next flight. A policy function approximation algorithm was presented based on geographical districts to decide whether an order was delivered by a UAV or by a truck. They showed that the operational costs serving the majority of customers were reduced by a combined fleet of UAVs and trucks in comparison to the truck-only case.

3.1.2. SUGV

Contrary to UAVs, SUGVs have scarcely been analyzed in the context of direct delivery because of their lower speed and shorter geographical reach compared with UAVs. Instead, they are more often addressed in a collaborative configuration with other vehicles. Under the direct delivery concept, SUGVs are supposed to serve only customers who are located nearby the warehouse [47].

We want to point out that since high-payload SUGVs potentially may carry several deliveries, the use of delivery bots in a multi-stop direct drone delivery concept as suggested by [48] is an option for SUGV use, too (see Figure 3b). They analyzed the sole application of SUGVs in the context of urban parcel delivery. SUGVs having independent compartments were loaded in stations and dispatched for customers. Between two tours, SUGVs had to be reequipped with full batteries. They presented a location routing problem with the main goal of minimizing the total daily costs including rental cost of SUGVs, personnel cost for loading drones, and delivery cost. By solving the model, they decided how many SUGVs should be assigned to which station and in which sequence customers were served by SUGVs. Restrictions regarding battery capacity and time windows were considered. Although this option does not require other vehicles, we suggest differentiating this concept from the conceptual type of single-stop direct drone delivery (see Figure 3a) and to assign this multi-stop concept to the classical vehicle routing concepts instead.

3.2. Indirect Drone Delivery (via Stationary Mini Hub)

Battery capacity, and thus geographical reach, is a significant challenge for drone delivery. One option to solve this challenge is to build cross-docking points (also called mini-hubs, micro-depots, or drone stations) between the central warehouse and the end customers to shorten the drone routes. This indirect drone delivery concept combines the use of drones and other vehicles and is depicted in Figure 4. This concept divides deliveries into two tiers. The first "long-haul" transport (tier 1) from the central warehouse to mini hubs could be performed by vehicles such as conventional or electrical vans. SUGVs and/or UAVs are based at the mini-hubs and operate between the mini-hubs and the drop points (tier 2). These mini-hubs usually do not require much costly urban space [49] and could be implemented in a container [50].

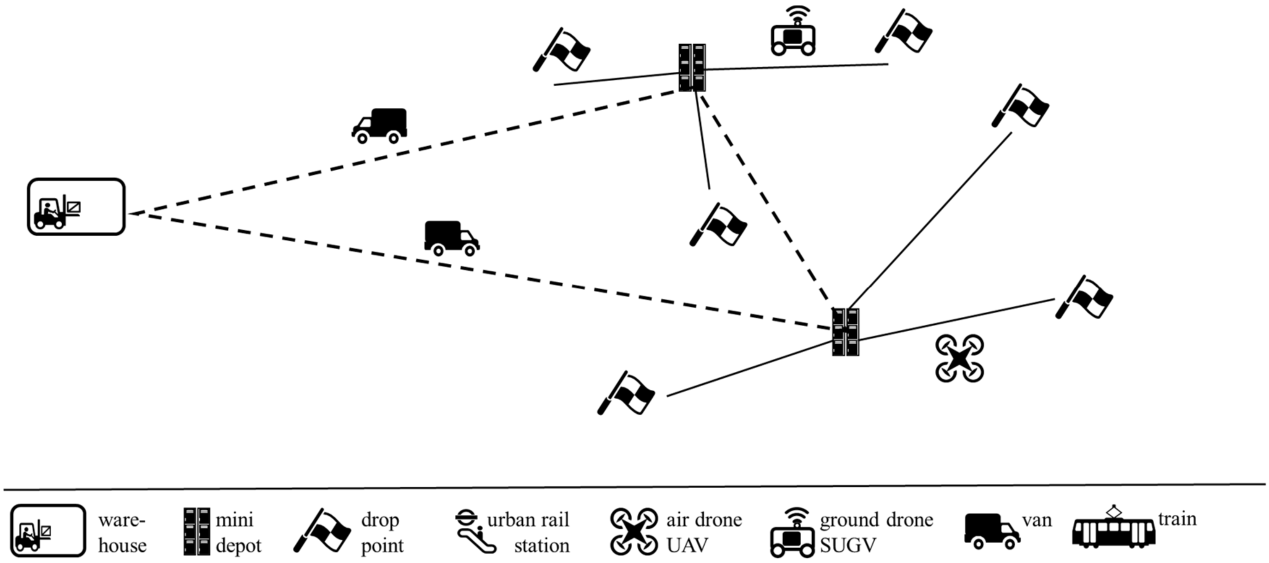

Figure 4. Delivery concept: indirect drone delivery via mini hubs.

Literature related to this concept is referred to below in ascending order of the publication year.

3.2.1. UAV

Ref. [50] constructed a two-level facility location problem for emergency medical supply. Conventional trucks were used to transport goods from the central warehouse to nests and each nest served a customer cluster with UAVs. Each UAV delivered one parcel in each round. Considering a maximal budget for the network operation and the UAV battery duration, the locations of the warehouse and nests were either generated by minimizing the total demand-weighted delivery time (model 1) or by minimizing the maximum demand-weighted delivery time (model 2).

Ref. [51] investigated the co-use of UAVs of different sizes. UAVs with a larger capacity transport packages in the first tier and smaller UAVs delivered them in the second tier to customers. They introduced a heterogeneous UAV fleet routing problem to optimize this type of operation.

Ref. [49] investigated a truck–drone system to overcome the flight range limitation and proposed a so-called traveling salesman problem with drone stations (TSP-DS) to decide which customers shall be served in the first-tier vehicle and which customers shall be served in a second tier by drones.

We want to point out that in addition to the indirect drone delivery concept depicted in Figure 4, ref. [52] proposed another concept wherein delivery trucks are regularly resupplied by UAVs, given that UAVs fly faster than trucks. Resupply can take place whenever a delivery truck is stationary and a UAV can land on the truck's roof. This novel way was introduced to exploit UAVs in same-day home delivery settings and it was tested by Matternet and Mercedes-Benz in 2017 in Switzerland to serve on-demand delivery [53]. It was designed to avoid the need of more vehicles and drivers, or return trips to a distribution center. The approach also neatly sidesteps the issue of having customers interact with UAVs at their front door. Although this concept also includes aspects of indirect delivery, we suggest not including this concept in the conceptual type of indirect drone delivery but rather to assign this concept to innovative vehicle routing concepts instead.

3.2.2. SUGV

Ref. [54] simulated indirect parcel delivery operations with SUGVs, where parcels in the central warehouse were heuristically assigned to either indirect SUGV delivery or to direct truck delivery. Parcels assigned to SUGV delivery (a small percentage of total demand) were consolidated by truck in the first tier and transported to micro-depots (e.g., kiosks, supermarkets, etc.) from which SUGVs delivered the parcels to customers in the second tier. The other parcels were assigned to conventional truck delivery. Each micro-depot was equipped with only one SUGV. The queued orders at a micro-depot were then processed one after another by the SUGV.

Ref. [55] proposed that robot hubs (i.e., mini-depots where SUGVs are stationed) could be filled by conventional trucks with large volume packages in late evenings or early mornings and SUGVs delivered packages to customers during the day to make the best use of the advantages provided by both vehicles. SUGVs were limited to one package per delivery and they could perform multiple pendulum tours between robot hubs and individual customers during the day. Upon each return to the robot hub, the SUGVs need to recharge their battery to full capacity. They presented mixed-integer programs to locate robot hubs and decided the number of SUGVs for each hub by minimizing the total operation costs, which included gas and driver costs for the first tier and electricity costs for the second tier. Time for loading and recharging was considered. Different scenarios were analyzed, for instance, with and without a time window, and in downtown or suburban areas. Results indicated that costs per package for the two-tiered robot-based deliveries were significantly lower compared with the costs of a conventional single-tier truck-based system across all experiments.

3.3. Mothership Drone Delivery (via Mobile Piggybag Carrier)

The indirect drone delivery concept can extend the reach of delivery drones but requires investment into fixed mini-depot facilities. The expenditure increases as the needed number of mini hubs increases. Another concept to increase the range of delivery drones which avoids budgets for building and operating mini hubs is the mothership drone delivery concept. The mothership vehicle operates as a mobile storage and launching platform under this concept. Depending on which kind of vehicle is used as the mothership carrier, two primary subcategories of the mothership drone delivery concept are generalized in this section: drone delivery via drone carrier van and drone delivery via public transport.

3.3.1. Drone Delivery via Drone Carrier Van

A general idea of the van mothership drone delivery concept is depicted in Figure 5. Drones are launched from the mothership van which is loaded at the central warehouse and performs a delivery round trip. While the drones perform their single-customer delivery routes, the truck moves to the next "reuniting location" while it serves other customers itself. After the reuniting, drones are re-loaded with a parcel (and in case of need are equipped with a fully loaded exchange battery) for subsequent deliveries. There are several variants of this concept.

Literature related to this concept is referred to below in ascending order of the publication year.

UAV

Ref. [56] were the first to introduce the van mothership UAV delivery concept to the operation research community. They presented a model where one UAV and one van collaboratively served all customers. In this model, each customer node was only visited once either by van or by UAV. They assumed the UAV was able to load only one unit for a flight and it was only possible to launch the drone at stationary locations (e.g., depot, customer locations). The UAV reunited with the van after each delivery. By minimizing the total delivery time, assignment decisions (which vehicle serves which customer) and routing decisions (in which sequence customers are to be visited) were made.

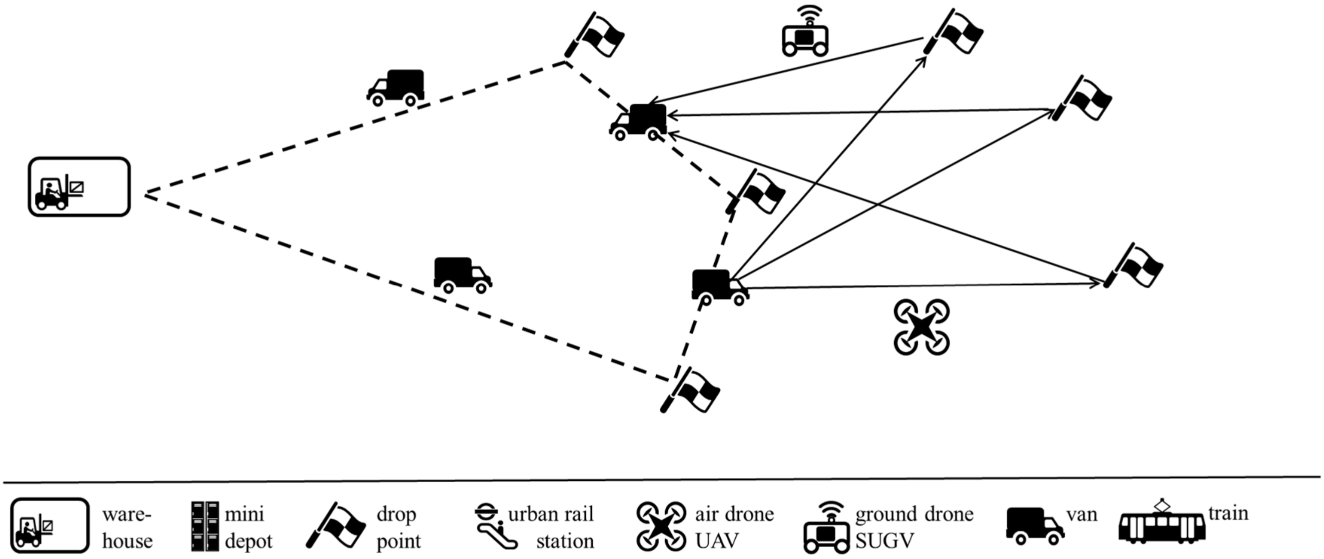

Figure 5. Delivery concept: drone delivery via drone carrier van.

Ref. [57] analyzed a hub tandem configuration involving one truck and multiple UAVs. The truck waited for UAVs at the same stop where they were launched. Customers at the stop were served by the truck driver while UAVs delivered parcels to customers in the nearby locations. Each UAV was supposed to carry only one shipment when airborne. The constraint of UAV battery range was neglected. The objective was to find the optimal number and locations of truck stops by optimizing the total delivery time and energy consumption, respectively. Results showed that the tandem mode was time-efficient compared with the truck-only mode if the speed of the UAV was approximately three times (or more) that of the truck or if two or more UAVs were assigned to each truck. The tandem mode was found as always more energy efficient than the truck-only mode even considering the return of UAVs to the truck.

Ref. [58] analyzed a general case where n customers were to be served by a homogeneous fleet of m trucks, each carrying k UAVs. Every customer demanded one parcel, which could be delivered either by a truck or by UAV. A UAV could carry at most one parcel at a time and was always able to fly to any customer within the reach of one battery life. UAVs could be launched and/or picked up by the trucks at the depot or any of the customer locations. Identical distance metrics were applied for trucks and UAVs because UAVs were assumed to fly over streets only (i.e., no beeline shortcuts). The objective was to minimize the maximum duration of the routes (i.e., the completion time) by adjusting the fleet size of both vehicles and varying the speed ratio of UAVs to trucks. The results showed that the total delivery time (including returning of empty vehicles) could be possibly reduced by 75% compared with truck-only delivery when UAVs traveled 50% faster than trucks and at most two UAVs per truck were employed.

Ref. [59] indicated that the time savings of the mothership delivery were up to 34.1% compared with the truck-only mode if the UAV speed was three times higher than the truck speed for a one-UAV one-truck setting. Ref. [60] demonstrated that the improvement in time efficiency was proportional to the square root of the ratio of the speeds of the truck and the UAV. Ref. [61] scheduled the optimal drones' routes based on a given route of the mothership truck and decided the drones' number on the truck. Ref. [62] considered the time components for loading, battery replacement, and service to customers in the objective function.

We want to point out that ref. [63] modeled a "one truck plus one UAV" configuration where the UAV was allowed to visit multiple customers within its battery range. We consider this concept to show significant differences from the mothership concept as depicted in Figure 5, as the drone needs to be a heavy load drone to carry multiple parcels in the first place, and the nature of the optimization problem changes because of the multi-stop nature of the drone route.

SUGV

Ref. [64] introduced a mothership operation process where SUGVs were first dropped at predefined stops in the service area and collected again by the van at the same stops. Customers were only served by SUGVs. The Mercedes Benz–Starship prototype was used in the case study as the mothership van, which carried eight SUGVs on board at a time. While the first batch of SUGVs was underway to serve the relevant customers, instead of waiting for their return, the mothership van went back to the central warehouse to pick up a second batch of SUGVs. The second batch of loaded SUGVs was released while the first batch of now empty SUGVs was picked up simultaneously. The van then transported the first batch of SUGVs back to the central warehouse for later recharging and re-loading and then drove again to the service area to pick up the second batch of SUGVs. A large fleet size of SUGVs was assumed to be available at the central warehouse. Loading, offloading, and service time at customer locations were considered. Results showed that the mothership delivery could make significant time and operational cost savings compared with the truck-only mode if the same preparation time (e.g., parking, launching) were assumed for both modes. However, the adoption of SUGVs would be less effective in terms of energy consumption when service areas are located farther from the depot since the energy consumption of the eight SUGVs is a small fraction of the energy consumption of the mothership van [47].

Ref. [65] analyzed a mothership delivery variant with the use of SUGV depots. The truck transported several SUGVs as well as goods on board and dropped SUGVs at different stops to launch their deliveries. Each SUGV carried one shipment at a time. The SUGVs returned autonomously to the nearest SUGV depots for recharging and parking. After dropping all boarded SUGVs, the truck picked up empty SUGVs at the depots, loaded them, and launched them again for the next round. It was assumed that enough SUGVs were available at depots to be picked up. This process was called R2D (robot to depot). Contrary to R2D, the truck had to await the returns of SUGVs by R2T (robot to truck). In both modes, customers were exclusively supplied by SUGVs. The presented results showed that the R2D policy considerably outperformed the R2T.

We want to point out that this specific mothership concept variant is different from the concept presented in Figure 4 and bears significant similarities to the indirect delivery concept as depicted in Figure 3 from an optimization problem formulation point of view.

3.3.2. SUGV Delivery via Public (Night) Transport

Ref. [66] reported the “Logistiktram” project in Germany. The project analyzed connecting trams and bicycles to perform last mile delivery. They composed four logistics boxes into one mobile depot which was transported by trams to predefined stations. People used a special designed trailer to load one logistics box behind their bicycles and ride through the last mile to end customers. Mobile depots were taken away again by trams after several hours from the stations.

Inspired by this idea, we suggest using means of public transport as motherships for SUGVs during “non-peak” hours. Public trams and subways in the cities have the advantages of running fast and frequently and having large capacities, which could be shared by human passengers and SUGVs. SUGVs could reach customers automatically and efficiently within short ranges from the nearest public transport station. Co-using existing public transport systems, especially at night time, can increase the reach range of SUGVs without generating additional street traffic.

Figure 6 depicts the co-use of urban railways. Loaded SUGVs proceed into trains at the station close to the central warehouse and are transported to other stations close to their destinations. SUGVs can stay in an energy-saving standby mode while being carried to their relevant offboarding stations. At these predefined stations, they automatically disembark the train, take elevators or escalators if necessary, and move to their drop-off points on sidewalks. After delivery, they proceed back to the warehouse the way they came.

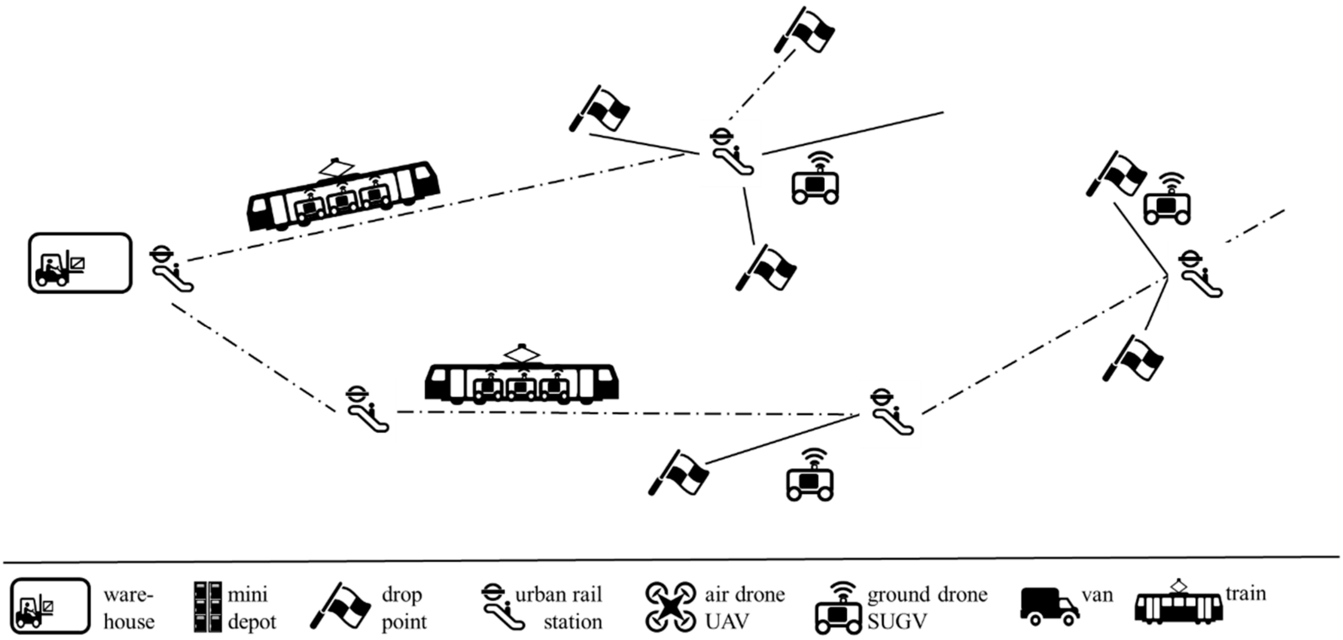

Figure 6. Delivery concept: SUGV delivery via public (night) transport.

A prerequisite of this concept is the ability of the SUGV to autonomously use existing devices (e.g., elevators or escalators) to perform vertical movements. Thus, the SUGV needs to either be equipped with a remote control to operate elevators or needs to be able to use escalators. Thus, attempts are made to enable SUGVs to use elevators (e.g., the Japanese delivery robot DeliRo [67] and the Dutch delivery robot Relay [68]. Simultaneously, elevator manufacturers (e.g., Thyssenkrupp) are launching elevator interfaces for delivery robots [69].

4. Technology Overview

In this chapter, a set of five UAV models and a set of five SUGV models for last mile delivery are selected to provide a non-exhaustive overview of existing technologies. Within each set, the drone types are compared with respect to the key technical characteristics related to the payload, reach, speed, and noise emission.

4.1. UAV

Table 1 provides the technical parameters of five UAV models.

Fixed-wing UAVs adopted by DHL and Zipline have a significantly farther reach range and higher cruising speed compared with the quadrocopter and octocopter UAVs employed by Matternet, Flirtey, and Emqopter.

According to the max. take-off weight, all UAVs fall into the same category (4–25 kg) of license class C3 and C4, as defined by the European regulations for UAV operation [70].

The number of compartments/chambers defines the number of deliveries per trip. Although research work has proposed that serving multiple customers on a round trip would increase delivery efficiency, the UAVs in Table 1 are only equipped with one compartment.

The information on loading and offloading methods is derived from the latest technology adopted by each company. Zipline and Matternet load packages (medical supplies) manually in their UAV operations. A ground worker is needed to load the package into the chamber (Zipline) or fix the package under the UAV (Matternet). Zipline uses a parachute to offload its package without the need of landing the UAV. Matternet lands the UAV first and requires another ground worker to unload the package. DHL and Flirtey adopt automated ground stations (so-called skyports) to load and launch their UAVs. The ground station of DHL is a combination of a mailbox and a helipad. Customers just need to place their packages in one box in the station, and then the package is loaded automatically into the chamber of the UAV. On arrival, the DHL UAV lands on the roof of the ground station where it is automatically unloaded, and the goods are stored in a specific box for customers to pick them up. Flirtey applies a similar ground station concept to load and launch their UAVs. For delivery, it "drops" packages at customers by a rope and customers need to take down packages from the hook.

Table 1. Technical aspects of UAVs.

	DHL *	Zipline	Matternet	Flirtey	Emqopter
Type of vehicle	fixed-wing tiltrotor	fixed-wing multi-rotors	quadrocopter	quadrocopter	octocopter
Max. take-off weight	12 kg	20 kg	13.2 kg	10 kg	11 kg
Payload	4 kg	1.75 kg	2 kg	2 kg	1.5 kg
No. of compartments	1 (inside)	1 (inside)	1 (outside)	1 (inside)	1 (outside)
Loading method	skyport	manual	manual	skyport	manual
Offloading method	skyport	parachute	manual	rope	manual
Cruising Speed	130 km/h	100 km/h	57.6 km/h	20 km/h	20 km/h
Battery last	65 km	160 km	20 km	5 km	5 km
Battery build type	unknown	unknown	unknown	unknown	swappable
Noise emission	unknown	unknown	unknown	unknown	72.4 dB at 10 m

*: Parameters are provided for the parcelcopter 4.0.

As of today, little information on noise emissions is provided by each company. Following the noise test of Wing's operations in June 2019 in Gungahlin, the department of infrastructure, transport, regional development, and communications of the Australian government has assessed the noise level produced by the UAV at 69 decibels at 15 m, with the delivery process being completed within 45 s [71].

4.2. SUGV

Table 2 provides the technical parameters of five SUGV models.

The SUGVs we checked (see Table 2) are heavier and are designed to move at slower speeds (which enables them to co-use sideways at pedestrians' speed). Thus, they can deliver significantly heavier goods compared with UAVs,

In addition, the high total payload capacity of SUGVs could theoretically be divided into multiple compartments each serving one customer, thus offering the opportunity to optimize the whole delivery efficiency without losing the theft security (provided that it is technically granted that customers can only access their own compartment).

As of today, in all examples of Table 2, manual handling is required to load and offload SUGVs. This implies that customers must be present to receive the delivered goods.

Table 2. Technical aspects of SUGVs.

	Starship	Dispatch	Robby	Domino's	Twins Wheel
Weight	23 kg	unknown	27 kg	unknown	50 kg
Payload	10 kg	45 kg	unknown	9.5 kg	50 kg
No. of compartment	1	4	1	4 *	1
Loading method	manual	manual	manual	manual	manual
Offloading method	manual	manual	manual	manual	manual
Cruising speed	Max. 6 km/h	6 km/h	6 km/h	19 km/h	3.6/7.2 km/h
Battery last	6 km	77 km	32 km	19 km	15 km
Battery build type	swappable	unknown	unknown	unknown	built-in
Noise emission	unknown	unknown	unknown	unknown	unknown

*: all four compartments are accessible at the same time.

5. Commercial Assessment

To make a choice between UAVs and SUGVs for last mile delivery, last mile delivery service providers will need to assess the potential costs and understand the cost composition of applying both technologies. However, investigated literature in Section 3 addressed the topic of drone delivery primarily from the aspect of operational research, e.g., how to make strategic, tactical, and operational decisions for drone delivery networks to minimize the total delivery time. Actual drone costs (investment or operating costs) have rarely been discussed in detail.

To bridge this research gap, we suggest a general calculus template to assess the cost per shipment (CPS) as well as the cost per payload unit (CPP) for both UAV and SUGV delivery in the assumed context of direct drone delivery. For indirect drone delivery or mothership drone delivery, this calculus template only covers the second-tier costs, and first-tier costs will have to be added.

To identify cost drivers affecting this choice, we performed a ceteris-paribus (or one-way sensitivity analysis) on the base of two exemplary cost calculations for UAV and SUGV delivery, respectively. Finally, a full factorial design of the experimental approach was employed to calculate the effects of each cost driver.

5.1. Basic Assumptions

We assume that a last mile transport service provider is considering purchasing unmanned vehicles (i.e., UAVs or SUGVs) to perform last mile delivery for its customers. The unmanned vehicle is loaded at a mini-hub and delivers one package per shipment directly to each customer without any intermediate stops. The cost calculus is thus based on the following assumptions:

- Direct drone delivery between a mini-hub and customers (see Figure 3a);
- One package per shipment.
- Additionally, the following additional assumptions are made:
- One single drone as the basis for cost comparison (i.e., the number of needed drones, and the relevant investment volume are not considered in this cost calculus);
- Drones are used without interruptions except for battery replacement/recharging times (i.e., there are always enough shipments to be delivered, and no time windows of delivery are considered);
- Full battery for each delivery;
- Cargo handling costs at the mini-hub are neglected;
- Drones and batteries are linearly depreciated according to respective average lifetime mileages (i.e., we do not differentiate between fast and slow battery recharging schemes);
- Maintenance is conducted regularly to ensure high service quality; thus, maintenance costs are calculated per year;

- The average beeline distance between customers and the mini-hub is r.

Last but not least, we also make the following assumption for distance calculation. SUGVs follow the sideway infrastructure. Thus, the potential one-way travel distance of SUGVs is estimated with a beeline correction factor of $f = 1.27$ [72]. UAVs could theoretically fly beelines to customers, but they are subject to regulations regarding their flight path. According to U-space [73], they are not allowed to fly over private properties, offices, airports, factories and other buildings. Thus, we assume that UAVs will fly along public streets, and the same beeline correction factor $f = 1.27$ is used to evaluate the one-way travel distance of UAVs. Figure 7 presents the relationships of the used distance metrics.

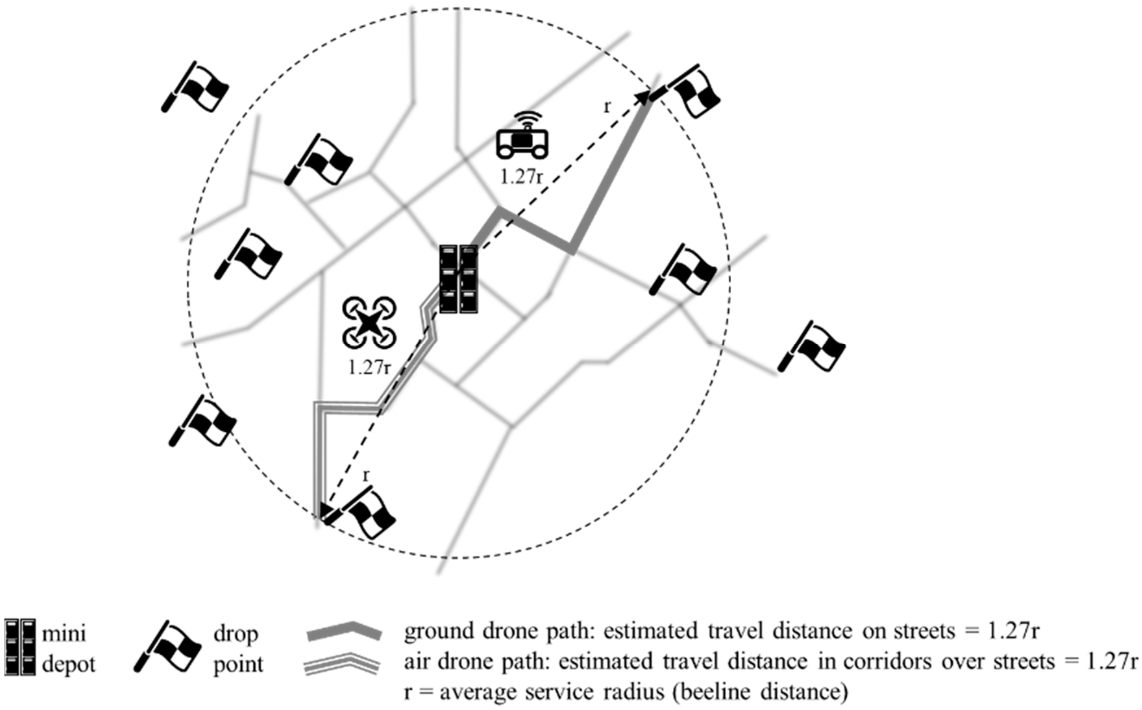

Figure 7. Travel distance calculation.

5.2. Cost Calculus Template

To calculate the costs of UAV and SUGV delivery, we introduce the following cost parameters and a cost calculation template.

5.2.1. Parameter Definitions

All needed parameters are listed as follows in alphabetical order:

d: working days per year (d/a);
e: energy consumption rate (KWh/km);
f: beeline distance correction factor;
h: working hours per day (h/d);
L_v: average lifetime of drones in mileage (km);
L_b: average lifetime of batteries in mileage (km);
m: drones per operator (i.e., how many drones can one operator handle simultaneously);
N: total amount of delivered shipments in a year ();
P: payload per drone (kg);
p_b: purchase price of one battery (EUR);
p_e: price of one unit of electricity (EUR/KWh);
p_i: annual insurance rate per drone (EUR/a);
p_m: annual maintenance costs per drone (EUR/a);
p_o: operator cost per hour for monitoring and control (EUR/h);

p_v: purchase price of one drone equipped with one initial battery (EUR);
r: average beeline service radius between customers and the mini-hub (km);
t: average total time needed for shipping one shipment (h);
t_0: average payloads' loading and offloading times needed for one shipment (h);
t_r: average time for replacing one battery (h);
t_c: average time for recharging one battery (h);
t_d: average round trip cruising time needed for one shipment (h);
t_{tl}: average take-off and landing time of UAVs (h);
v: average cruising speed of drones (km/h);

5.2.2. Cost Calculus Template

For the cost analysis, the calculation template considers cost components according to the cost differentiation of ref. [74] from the aspects of staff, material (incl. vehicle hardware and software, battery, and energy), service (i.e., maintenance), and insurance. Capital cost (e.g., imputed interests and depreciations), cost of foreign rights (e.g., software licenses that are not provided together with drones), and taxes are not taken into account.

We suggest utilizing CPS as a metric for the cost comparison between UAV and SUGV delivery. Therefore, the above-mentioned cost categories have to be aggregated into unit costs (i.e., CPS). The energy cost and operator cost are calculated under the causation principle directly for each shipment, and the cost of drone, battery, maintenance, and insurance are allocated to each shipment according to the average principle [74].

The final CPS of UAV or SUGV delivery could then be formulated as follows:

$$CPS = C_{dv} + C_{db} + C_e + C_o + C_m + C_i \tag{1}$$

where each unit cost component is explained as follows:

- Vehicle cost per shipment (EUR): $C_{dv} = \frac{(p_v - p_b) \cdot 2 \cdot f \cdot r}{L_v}$ (the cost of the initial battery is deducted from the vehicle cost);
- Battery cost per shipment (EUR): $C_{db} = \frac{p_b \cdot 2 \cdot f \cdot r}{L_b}$;
- Energy cost per shipment (EUR): $C_e = 2 \cdot f \cdot r \cdot e \cdot p_e$ (supposing the energy consumption rate e is a comprehensive average of all flight phases including takeoff, cruising, hovering, and landing, including battery charging efficiency and engine efficiency as well);
- Operator cost per shipment (EUR): $C_o = \frac{t \cdot p_o}{m}$;
- Maintenance cost per shipment (EUR): $C_m = \frac{p_m}{N}$;
- Insurance cost per shipment (EUR): $C_i = \frac{p_i}{N}$.

The average time for one delivery is the sum of the payloads' loading and offloading time (t_0), round-trip driving time (t_d), and twice the take-off/landing time (t_{tl}).

$$t = t_0 + t_d + 2 \cdot t_{tl}$$

where $t_d = \frac{2 \cdot f \cdot r}{v}$ and $t_{tl} = 0$ for SUGV delivery.

In addition, we differentiated two battery build types to calculate the volume N of annual shipments by assuming drones are used without any interruptions except times for replacing/recharging batteries. That is, if drones are equipped with a swappable battery, they depart immediately for the next delivery after a quick battery replacement time. If drones are equipped with a built-in battery, delivery is suspended when drones are being recharged. Calculation formulas of N are given in Table 3.

As a result, for drones with a built-in battery, Formula (1) leads to

$$CPS = 2 \cdot f \cdot r \cdot \left(\frac{p_v - p_b}{L_v} + \frac{p_b}{L_b} + e \cdot p_e \right) + \frac{p_o}{m} \cdot \left(t_0 + \frac{2 \cdot f \cdot r}{v} + 2 \cdot t_{tl} \right) + \frac{(p_m + p_i)}{\left\lceil \frac{h}{t_0 + \frac{2 \cdot f \cdot r}{v} + 2 \cdot t_{tl} + t_c} \right\rceil \cdot d} \tag{2}$$

Table 3. Formulas of calculating annual shipments.

Battery Types	***N***
Built-in	$N = \left\lceil \frac{h}{t+t_c} \right\rceil \cdot d$ [1]
Swappable	$N = \left\lceil \frac{h}{t+t_r} \right\rceil \cdot d$ [2]

[1] $N = \left\lfloor \frac{h}{t+t_c} \right\rfloor \cdot d$, when $\frac{h}{t+t_c} - \left\lfloor \frac{h}{t+t_c} \right\rfloor < \frac{t}{t+t_c}$, otherwise $N = \left\lceil \frac{h}{t+t_c} \right\rceil \cdot d$. Depending on if there is enough time to perform another delivery at the end of the working hours in a day, the number of daily shipments is one more or one less. For simplification, we round the decimal up. [2] Processed the same as [1].

For drones with a swappable battery, t_c needs to be replaced by t_r in Formula (2).

Among all cost components, maintenance and insurance costs are currently the most difficult to be estimated as drone delivery has not yet reached a steady and state phase. To reduce the influence of parameters' uncertainty on CPS, Formula (3) excludes maintenance and insurance costs. This reduced cost formula can be applied for a basic calculation before robust data on maintenance and insurance costs are available.

$$CPS = 2 \cdot f \cdot r \cdot \left(\frac{p_v - p_b}{L_v} + \frac{p_b}{L_b} + e \cdot p_e \right) + \frac{p_o}{m} \cdot \left(t_0 + \frac{2 \cdot f \cdot r}{v} + 2 \cdot t_{tl} \right) \tag{3}$$

To roughly differentiate the impact of heavy and light average loads, we derived a second key performance indicator, CPP (cost per payload-unit (EUR/kg)), based on the assumption that each shipment employs the full payload of the drone:

$$CPP = \frac{CPS}{P} \tag{4}$$

All formulas in this section are generally defined for both UAV and SUGV delivery operations. Thus, by inserting model-specific parameter values, the calculus template provides CPS and CPP for both types of drone operations.

5.3. Exemplary Cost Calculus and First Tentative Cost Comparison

To provide numerical examples, we interviewed two companies, one small- and one medium-sized, from the drone manufacturing industry (one UAV manufacturer and one SUGV manufacturer). The SUGV manufacturer is specialized in producing heavy SUGVs. The UAV manufacturer provides small, standard delivery drones with a maximum take-off weight of under 15 kg. From each company, we took one standard model to perform an exemplary cost calculation in this section.

The commercial data for this exemplary calculus (Table 4) were orally provided by these two interviewed companies, and the missing data were added based on estimates made by the authors (for details on estimates, see the comments in Table 4).

The first calculus results of the two examples by applying the abovementioned input in Formulas (3) and (4) are depicted in Figure 8.

Considering a 2 km beeline service radius, the exemplary UAV delivery costs 1.44 EUR per shipment and the exemplary SUGV delivery costs 1.13 EUR per shipment. If the payload of each drone would be fully employed, i.e., 1.5 kg of the UAV, and 50 kg of the SUGV, the UAV delivery would cost 0.96 EUR per kg, and the SUGV delivery would cost 0.02 EUR per kg.

We want to point out that the comparison of CPS and CPP in Figure 8 is to be interpreted with extreme care, as it compares a lightweight air drone with a heavyweight delivery bot. Thus, this comparison might be criticized as comparing apples with oranges. Still, it is to be expected that lightweight delivery bots will be relatively inexpensive, and heavyweight air drones will be more expensive.

Table 4. Assumptions for the parameter values.

Parameters	Unit	UAV	SUGV	Comments
d	(d/a)	312	312	Assumption: 52 weeks per year × 6 days a week = 312
e	(KWh/km)	0.025	0.045	Fact: data provided by manufacturers
f	-	1.27	1.27	Assumption: based on [72]
h	(h/d)	16	16	Assumption: 6:00–22:00
L_b	(km)	75,000	30,000	Fact: no data provided by UAV manufacturer; data provided by SUGV manufacturer: batteries have a lifetime of about 3 years and drones of about 10 years Assumption: dividing drones' lifetime mileage by 10 years and batteries have 3 years of mileage for both UAVs and SUGVs
L_v	(km)	250,000	100,000	Fact: no data provided by UAV manufacturer; data provided by SUGV manufacturer: 100,000 km Assumption: 250,000 km for UAVs [75]
m	-	20 [1]	100 [2]	Assumption: see table footer
P	(kg)	1.5	50	Fact: data provided by manufacturers
p_b	(EUR)	1000	1600	Fact: 50 EUR–1000 EUR depending on capacity (data provided by UAV manufacturer); approximately 20% of vehicle price (data provided by SUGV manufacturer) Assumption: conservative estimate 1000 EUR for UAV and 1600 EUR for SUGV
p_e	(EUR/KWh)	0.3	0.3	Fact: the average day-ahead wholesale electricity price in 2020 [76]
p_i	(EUR/a)	0 *	0 *	* Assumption: as maintenance and insurance rates for this use case are currently evolving and presumably yet not in a robust steady state, we assumed identical rates for both the UAV and SUGV and neglected these two factors in our total cost calculus.
	(EUR/a)	0*	0*	
p_o	(EUR/h)	32 [3]	32 [3]	Assumption: see table footer
p_v	(EUR)	39,000	8000	Fact: data provided by interviewed manufacturers
r	(km)	2 [4]	2 [4]	Assumption: conservative estimate 2 km beeline radius for both the UAV and SUGV, details see table footer
t_0	(h)	0.033	0.033	Assumption: 1 min for payloads' loading and 1 min for offloading
t_r	(h)	0.017	0	Assumption: 1 min for replacing the swappable battery; 0 min for the built-in battery
t_c	(h)	0.75	2.5	Fact: data provided by manufacturers
t_{tl}	(h)	0.033	0	Fact: 1 min for take-off, 1 min for landing (data provided by UAV manufacturer); 0 min for SUGV delivery
v	(km/h)	20	3.6	Fact: realistic cruising speed 20 km/h (oral information provided by UAV manufacturer); 3.6 km/h or 7.2 km/h (information provided by SUGV manufacturer) Assumption: conservative estimate 3.6 km/h for the SUGV

[1] Max. 20 to 1 is proposed by all 10 applications for a special-class-type certificate by the FAA [77]. [2] One operator is able to operate 100 Starships at the same time when running at 99 percent autonomous driving [78]. [3] We assume the drone operator qualification requires an average payment in Germany. Therefore, the formula to approximately calculate the average hourly personal cost for drone operation companies is as follows: $\frac{(gross\ salary\ per\ month + social\ insurance\ cost\ per\ month) \cdot 12\ month}{working\ hours\ in\ a\ year} = \frac{(3994 + 3994 \cdot 19.325\%) \cdot 12}{221 \cdot 8} \approx 32\ €/h$ Fact: the average gross salary of full-time employees per month in Germany in 2019: 3994 EUR, and the social insurance cost (payment of employer) in percent of gross salary in Germany in 2020 is 19.325% (including pension insurance 9.3%, health insurance 7.3%, unemployment 1.2%, and care insurance 1.525%) [79]. Assumption: 221 working days in a year (365 days deducting 104 weekend days, 10 public holidays, and 30 private vacation days), 8 working hours in a day (note: operators work in shift to complete drones' workload in 312 days × 16 h). [4] Fact: realistic cruising speed 20 km/h, max. one way operation distance 3 km, standard battery reach 15 min (data provided by UAV manufacturer); max. total travel distance 10∼15 km (data provided by SUGV manufacturer). Assumption: beeline correction factor 1.27. The two formulas to calculate the max. beeline radius of UAV are as follows: $\frac{3}{1.27} = 2.36$ km, $\frac{20 \cdot 15}{60 \cdot 2 \cdot 1.27} = 1.97$ km; the formula to calculate the max. beeline radius of SUGV is as follows: $\frac{10 \sim 15}{2 \cdot 1.27} = 3.94 \sim 5.9$ km. Therefore, a conservative estimate of 2 km is assumed for the average beeline service radius of both the UAV and SUGV.

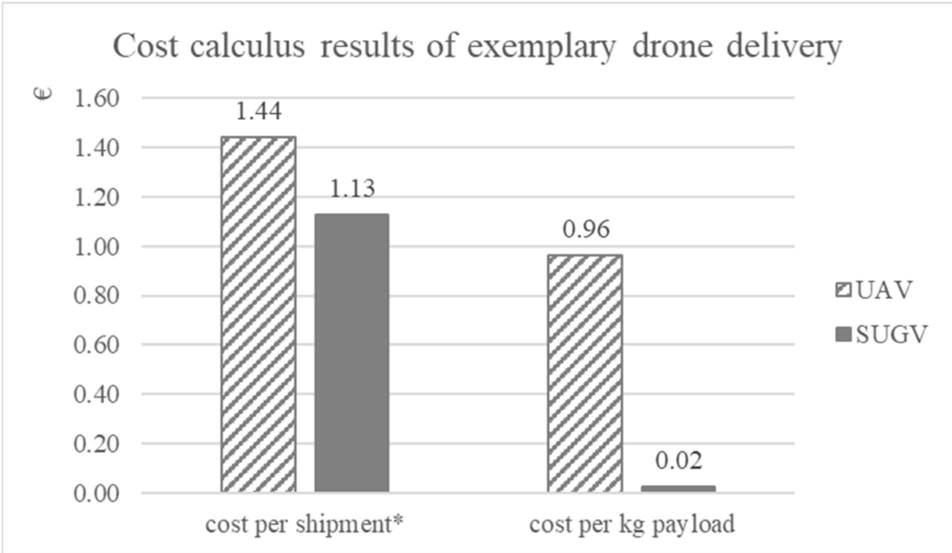

Figure 8. Cost calculus results of exemplary drone delivery (Please note this first result depends very strongly on the cost parameter assumptions in Table 4). *: shipment with a 2 km beeline radius.

5.4. One-Way Sensitivity Analysis

To discern cost drivers, i.e., which parameters play significant roles in affecting the CPS result of the calculus, this section provides a classic one-way sensitivity analysis [80] by varying parameters' values one at a time while keeping others constant. Given the calculus model provided in Section 5.2.2, we consider one-way sensitivity analysis as an adequate method to reveal the relative influence of each input parameter on the output of the model. We increased and decreased parameters separately by 50% and recorded the percent change of CPS. Figures 9 and 10 depict the results of the one-way sensitivity analysis of CPS for UAV delivery and SUGV last mile delivery, respectively.

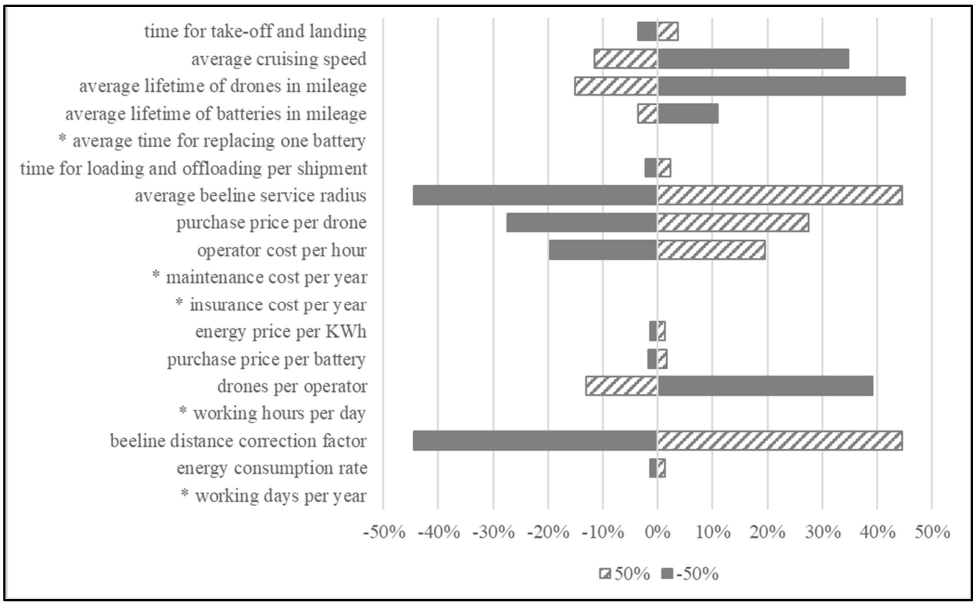

Figure 9. One-way sensitivity analysis of CPS for UAV last mile delivery (Tornado plots). *: parameters were excluded from the one-way sensitivity analysis.

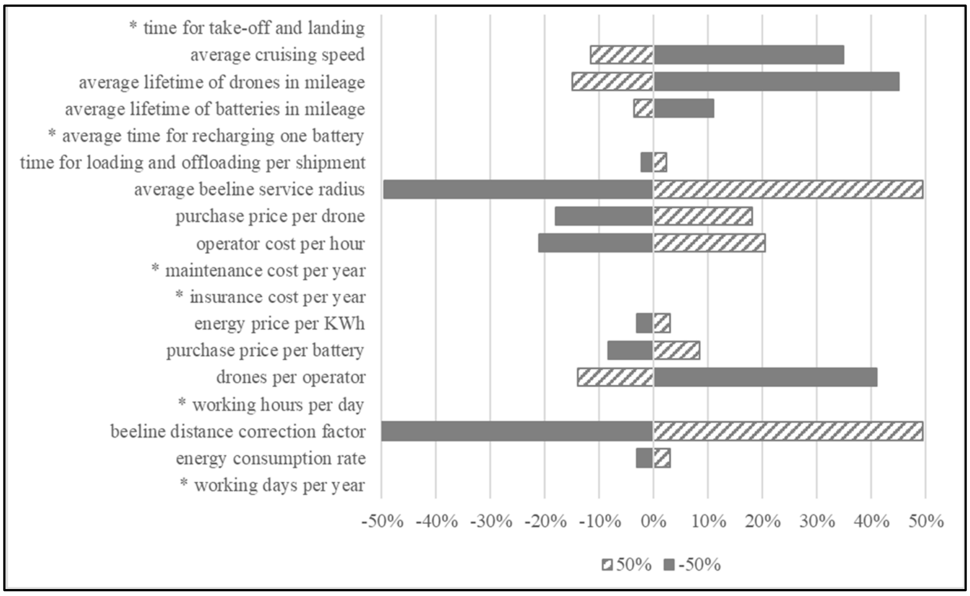

Figure 10. One-way sensitivity analysis of CPS for SUGV last mile delivery (Tornado plots). *: parameters were excluded from one-way sensitivity analysis.

The *x*-axis in both figures presents the CPS change in percent based on the first result (shown in Figure 8) when each investigated parameter was increased or decreased by 50%, respectively. The Y axis lists all 18 parameters involved in the cost calculus, respectively, for UAV and SUGV delivery. Among all, 13 parameters of UAV delivery and 12 parameters of SUGV delivery were investigated in the one-way sensitivity analysis. In both cases, the annual maintenance cost p_m and annual insurance cost p_i were excluded from one-way sensitivity analysis since adequate initial data were missing. Therefore, all other auxiliary parameters needed to calculate maintenance and insurance cost per shipment (i.e., working hours per day h, working days per year d, and average time of battery recharge/replacement t_c, t_r) were excluded from the one-way sensitivity analysis as well. In addition, time for take-off and landing t_{tl} was also neglected in the one-way sensitivity analysis for SUGV delivery as for SUGVs this time component is already included in t_d.

There were five identical parameters in both modes, resulting in a CPS change of at least 30% when each of them increased or decreased by 50%. They are average cruising speed v, average beeline service radius r, average lifetime of drones in mileage L_v, drones per operator m, and the beeline distance correction factor f. We thus consider these as significant cost drivers for drone delivery.

Three parameters resulted in a CPS change between 10% and 30%. They are as follows: average lifetime of batteries in mileage L_b, purchase price of a drone p_v, and operator cost per hour p_o. We thus consider these as slightly significant cost drivers for drone delivery.

The remaining parameters resulted in a CPS change of less than 10% in both modes when each of them was increased or decreased by 50%. They are as follows: time for loading and offloading per shipment t_0, energy price per KWh p_e, energy consumption rate e, and purchase price of battery p_b. Therefore, we do not consider them to be cost drivers. For UAV delivery the time for take-off and landing t_{tl} belongs to this category, too.

5.5. Full Factorial Design Approach

Although the above ceteris-paribus (or one-way sensitivity analysis) provides a first answer to the question of which cost elements can be considered as cost drivers, its results are based on the initial values of each cost parameter. To confirm these results, we conducted a full factorial design of experiments approach in accordance with the methodology presented by ref. [81], and systematically assessed cost parameter value setting combinations. For this approach, we defined plausible high and low values for the seven most relevant cost drivers identified in the one-way sensitivity analysis and evaluated all possible parameter combinations (for details, see Table 5).

The results of this analysis regarding the average effect of each cost driver over all analyzed cost parameter scenarios are depicted in Figures 11 and 12.

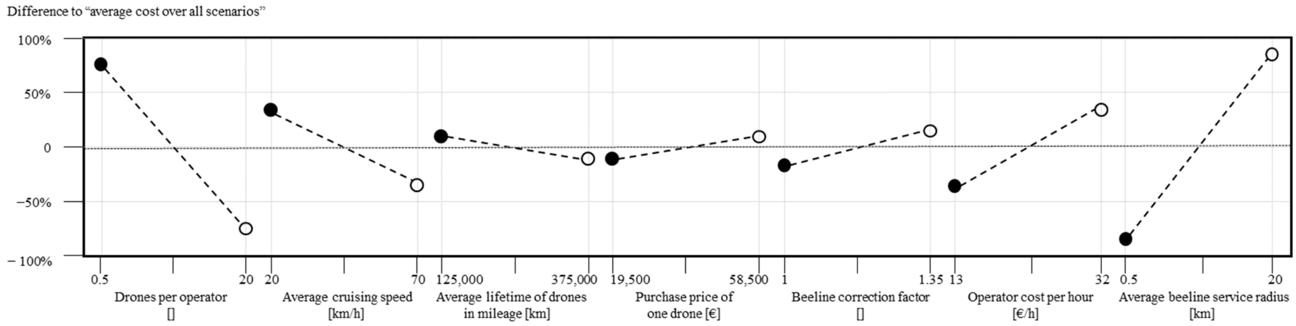

Figure 11. Effect diagram of cost drivers on CPS of UAV delivery.

Figure 12. Effect diagram of cost drivers on CPS of SUGV delivery.

The x-axis represents the analyzed cost drivers with both low and high design values as defined in Table 5. The y-axis represents the difference to the “average CPS value over all possible cost parameter combinations“, which is represented by the horizontal dashed line (y = 0) of each diagram. Points in black depict the average change of CPS if the factor was set to its low value. Points in white depict the high value. The CPS difference between the two connected points reflects the effect of the respective cost driver over the given low–high range on the CPS of drone delivery.

Generally, it was confirmed that drones per operator m, average cruising speed v, and average lifetime of drones in mileage L_v reduced the CPS of drone delivery, while the cost of a drone p_v, operator per hour p_o, beeline correction factor f, and average beeline service radius r increased the CPS of drone delivery.

5.6. Summary of Commercial Results

Figures 11 and 12 show that the factors “drones per operator” m in combination with “operator costs per hour” p_o as well as “average beeline service radius” r in combination with “average cruising speed” v demonstrated the most significant changes; thus, their roles as important cost drivers is confirmed.

The cost drivers “drones per operator” m in combination with “operator costs per hour” p_o are also plausible from a domain-know-how point of view, because the more drones one operator can handle in parallel, the lower the operator costs per delivery. Assuming one operator can handle more delivery bots than air drones in parallel at a time, these cost drivers promote delivery bot delivery concepts.

The cost drivers of “average beeline service radius” r in combination with the “average cruising speed” v have an impact on the utilization of operators, too, as lower speeds, as well as longer distances, induce longer average delivery times and thus result in more drones needed in parallel; consequently, more operators are needed. Assuming that air drones can operate at higher speeds than delivery bots, these cost drivers promote air drone delivery concepts. (SUGV operations during daytime at 3.5 km/h are roughly twice as expensive as a SUGV operation at nighttime at 7.0 km/h (see Figures 11 and 12)).

Table 5. Intervals of cost drivers.

Impact Factors	Unit	UAV		SUGV		Comments
		Low	High	Low	High	
f	-	1 *	1.35	1.1	1.35	The average range for city streets is 1.1–1.35 [72]. *:assumption: UAVs are allowed to fly straight
L_v	(km)	125,000	375,000	27,500	825,000	data are difficult to acquire, no extensive research on other manufacturers; we ad hoc estimate a 50% decrease of the exemplary parameter for low values and a 50% increase of the exemplary parameter for high values
p_v	(EUR)	19,500	58,500	4000	12,000	
m	-	0.5	20	1	100	Low values: data provided by interviewed drone manufacturers High values: see table footers 1 and 2 of Table 4
	(EUR/h)	13	32	13	32	Minimum monthly gross wage (1600 EUR) to average monthly gross wage (3994 EUR) of full-time employees in Germany 2019 [82];for the calculation, see table footer 3 of Table 4
r	(km)	0.5	20	0.5	20	Low values: we suppose a distance shorter than 0.5 km does not provide enough motivation for drone delivery. High values: most European cities have around 20 km radius, e.g., Berlin, Hamburg, London, and Paris (checked on Google Maps).
v	(km/h)	20	70 [1]	3.6	7 [2]	Low values: data provided by interview drone manufacturers High values: see table footers

[1] The max. speed under FAA regulation is 160 km/h [83]; we ad hoc estimate an effective cruising speed as 70 km/h by referring to the max. and average speed of drones in the market. [2] The max. walking pace allowed on pedestrian sidewalks is 5–20 km/h in Germany [84] and the max. design speed of motored wheelchairs is 15 km/h [85]. We assume an optimistic average speed could be 7 km/h.

6. Environmental Assessment

This chapter focuses on two environmental aspects only: noise emissions and operative energy consumption. Noise is considered because this aspect will either be no issue (if drone-induced noise levels are low enough) or it will result in protests from urban residents (if drone noise levels reduce the urban life quality significantly). Operative energy consumption is considered because as long as we produce electricity from fossil sources, energy consumption contributes to global warming (depending on the energy mix to produce electricity).

6.1. Noise

The noise of UAVs is being discussed as a concern of the public. Unlike SUGVs operating on the ground, the noise of UAVs comes from above makes it impossible to employ, e.g., noise reduction walls or street tunnels. UAVs emit noise in every flight phase: take-off, cruising, and landing. However, many UAV manufacturers today prefer to avoid talking about noise or providing any detailed data about it except for claiming that UAVs flying at around 100 m above ground would cause minimal disturbance to people living on the ground.

Data provided by an interviewed UAV manufacturer state a noise emission level of 72.4 dB for an air drone at a distance of 10 m.

The sound emitted by a sound source decreases with distance from the source. For point sources, the noise level decreases by 6 decibels per doubling of the distance, but for line sources, it only decreases by 3 decibels [86]. Based on this simple information, we roughly illustrate the noise spreading schemes of one single UAV and of a chain of UAVs flying along the same corridor.

Figure 13 depicts the noise emission scheme of a single UAV and Figure 14 illustrates the scheme of a "drone traffic corridor". Both figures assume the drones fly at a level of 80 m over the ground. Figure 15 illustrates the decibel scale of common noise sources in order to shed a light on how the UAV noise levels are perceived at ground level.

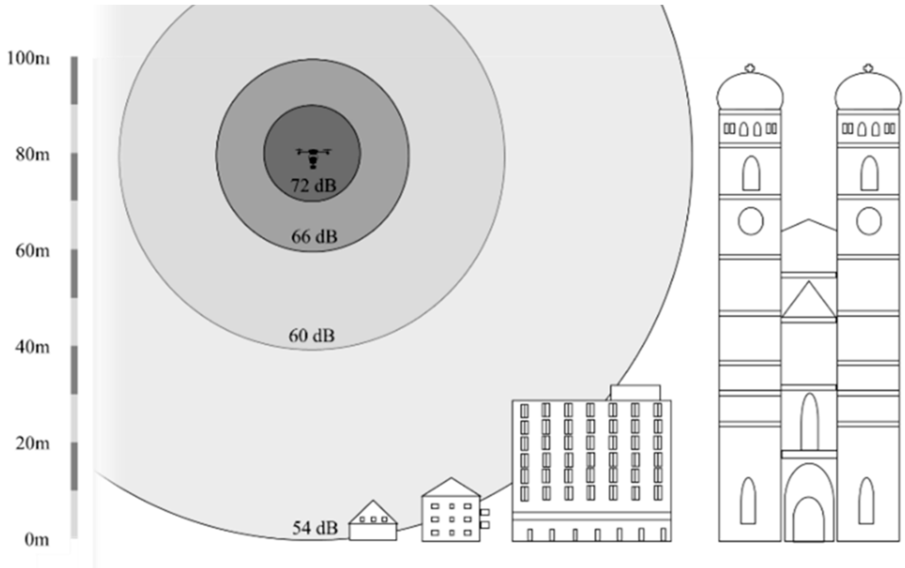

Figure 13. Noise emission scheme—point source.

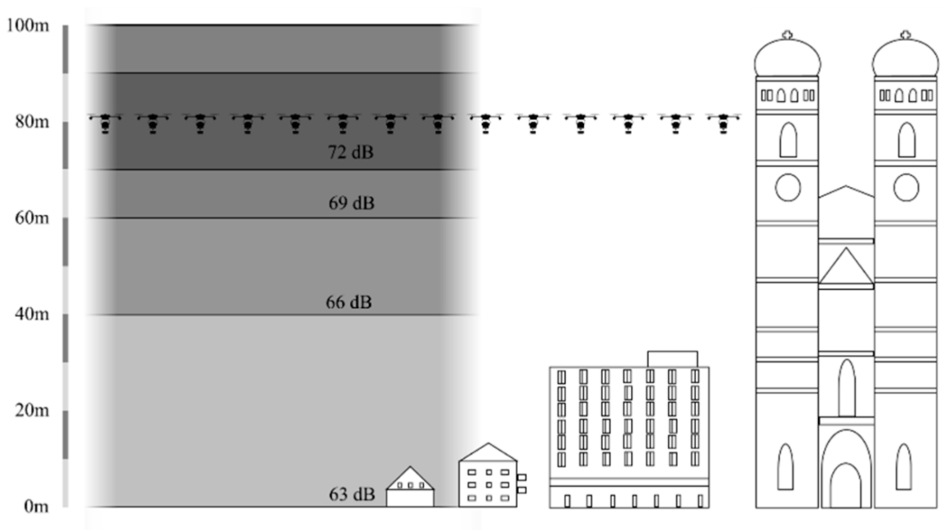

Figure 14. Noise emission scheme—line source.

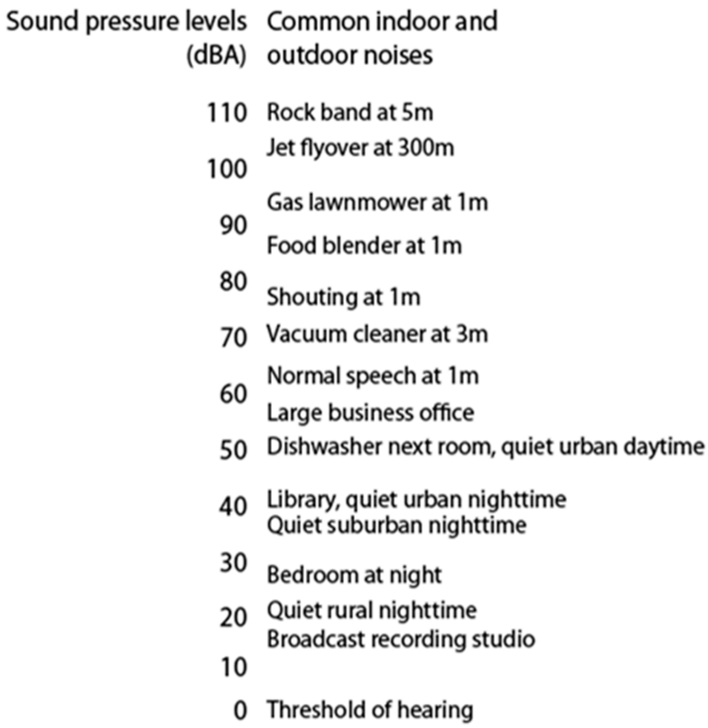

Figure 15. Decibel level of common noise sources [87].

As shown in Figure 13, one UAV flying at the height of 80 m as a point source produces a sound pressure level of around 54 dB at ground level, whereas a chain of UAVs flying at the height of 80 m as a line source produces a sound pressure level of around 63 dB at ground level and 66 dB at 40 m above ground (Figure 14). In addition, during take-off and landing, a UAV will produce a sound pressure level of 72 dB at a 10 m radius.

Referring to the decibel scale of common noise sources in Figure 15, 54 dB feels like a normal conversation, and 63 dB feels like the sound of a nearby vacuum cleaner. For average noise exposure, the World Health Organization (WHO) guideline development group strongly recommends reducing noise levels produced by road traffic to below 53 dB, as road traffic noise above this level is associated with adverse health effects [88].

Thus, when the traffic of UAVs becomes dense along dedicated flight corridors, the noise emissions can be assumed to have a significant negative impact on the well-being of urban citizens living or working nearby.

Compared with UAV noises, SUGVs emit significantly less noise. In a small experiment [89], we recorded a sound pressure level of 9 dB at a 1 m distance from the SUGV and of 4 dB at a distance of 10 m when the SUGV moved at a speed of 3.6 km/h. At a double speed of 7.2 km/h, we recorded a sound pressure level of 19 dB at a 1 m distance and 14 dB at a distance of 10 m from the SUGV. Thus, we assume that noise emissions of SUGVs can be neglected in comparison with UAVs.

6.2. Energy Use

In this section, we roughly assess the energy use of drone delivery in terms of three metrics: energy use per unit distance, energy use per shipment, and energy use per kg payload.

To provide a tentative comparison between UAV and SUGV delivery, we used the same models and parameters as in the cost calculus in Section 5. Thus, the basis for our calculus is a delivery of one shipment from point A to point B with a beeline distance of r. The energy use is defined mainly by the energy consumption rate e of the used drone, the beeline distance r and the beeline correction factor f of the operating route, and/or the total weight of the drone incl. the payload of the drone P, ignoring other external influences such as weather.

Still, even if this calculus scheme is rather simple, it is difficult to obtain the relevant data on the parameter values. Therefore, we asked two manufacturers for their technical data and used the data of [90] for our dimension calculus.

Table 6 depicts the first tentative energy consumption dimensions which were generated by our approach.

Table 6. Energy use metrics of drones.

Parameters	Unit	UAV °	Light-Weight (LW) SUGV **	Heavy-Weight (HW) SUGV °
e	(Kwh/km)	0.025	0.025	0.045
* Energy use per shipment $e \cdot f \cdot r$	(Kwh)	0.064	0.064	0.114
* Energy use per kg payload − unit $\frac{e \cdot f \cdot r}{P}$	(Kwh/kg)	0.043	0.006	0.002

*: $f = 1.27$, $r = 2$ km, $P(UAV) = 1.5$ kg, $P(LW - SUGV) = 10$ kg, $P(HW - SUGV) = 50$ kg; ** Source: [90]; ° Source: manufacturer information.

Assuming that the used non-representative data at least allow a rough dimensional comparison between the three alternatives on energy use, we see the following tentative result. For lightweight deliveries, there seemed to be no significant difference in energy consumption per delivery between UAVs and SUGVs. However, the heavier the delivery goods are, the more beneficial SUGVs become (see energy use per payload unit in Table 6).

Still, as the data used are three single-parameter samples, only, and therefore they cannot be assumed to be sufficiently representative; further engineering research on drone energy consumption is needed.

7. Conclusions

We performed a comprehensive comparison between air drones and delivery bots (ground drones) from a practical, conceptual, technological, commercial, and noise emission perspective. The key findings from our comprehensive literature research are the following:

From a practical perspective, both technologies are currently on the verge of moving from a test environment phase into a commercial use phase, mainly in the field of parcel and grocery delivery, and medical supply deployment;

From a theoretical and technological perspective, both technologies are suited for automated home delivery, but their geographical scope is limited by their battery reach. To widen this geographical scope, both technologies can employ the so-called "mothership concepts". Whereas air drones usually employ vans as motherships, delivery bots could potentially co-use the existing means of public transportation (regional trains, metros, busses, etc.) during off-peak hours. Standardized automated unloading of both technologies is still an issue because of the lack of missing automated handling standards between drones and delivery bots on the one side, and reception boxes on the other side;

From a commercial perspective, we introduced a cost comparison template for both technologies, and we showed that the economic viability of both technologies depends primarily on the impact factors: "number of drones per operator" and average "beeline service radius";

From a noise emission perspective, delivery bots have significant advantages over air drones. Other environmental aspects still require further research.

7.1. Discussion

We now want to critically discuss the used methodology as well as the results and to identify the need for further research.

7.1.1. Selected Economical Aspects

The economical comparison of ground and air drones is a challenging task because of today's lack of publicly available data on costs. The cost parameters in our calculus cannot be deemed sufficiently robust because they were the only price parameters we could obtain, and the analyzed drone variants were significantly different in their design concerning speed (air drones fast, delivery bots slow) and payload (air drones low and delivery bots high). We also assume that costs per delivery (CPS) are subject to cost parameter changes and subject to future downward dynamics because of economy of scale effects. Thus, and as the initial cost results just show a temporary snapshot, we conducted a one-way sensitivity analysis identifying the cost drivers of the calculus. Finally, due to the lack of data, some cost elements had to be excluded from our calculus—especially costs for upstream logistics, investment costs for stationary devices (i.e., heliports and automated parcel boxes), and costs for drone maintenance and insurance. Still, considering all these shortcomings, we were at least able to come up with cost dimensions. The cost dimensions for delivery bot operations seem plausible with regard to externally charged costs as, e.g., reported by the Independent: "They typically pay £1 for each delivery, but in Milton Keynes, Starship has raised the price to as much as £2 during the busiest times in an effort to spread demand across the day" [91]. We were able to identify the relevant cost drivers.

7.1.2. Selected Environmental Aspects

As both drone types are electrically propelled, their CO_2 footprint very much depends on the technology used to generate electricity. A rough dimension check of the publicly available data provided by drone manufacturers seems to show no significant differences in energy consumption per delivery. Still, there is a need for further research with regard to an in-depth analysis of this aspect.

Noise, on the other hand, is a critical factor for the employment of air drones, which so far has been given rather little attention by lawmakers and scientists (compared, e.g., with the literature dealing with road and rail noise emissions in cities). Our first dimension checks showed a dimensional difference in noise emissions between air drones and delivery bots. Therefore, we see the need for further research on this issue to be conducted by acoustics specialists, and by urban planners on the questions of (a) if and how air drone noise emissions could significantly be reduced, (b) if and how citizens could be shielded from noise from above, and (c) if or not citizens are willing to endure additional noise exposure in exchange for faster home delivery services.

7.2. Other Needs for Further Research

Technology, concepts, costs, and environmental aspects are not the only relevant aspects if a choice between UAVs and SUGVs is to be made. The following aspects should be subject to further research, too:

- One aspect is customer convenience. Therefore, we see the need to elaborate further concepts to automatically hand over goods at delivery without the need for the recipient to be present. This would require, e.g., an infrastructure of parcel drop boxes with a standardized physical interface to drones for automated goods delivery;
- In addition, as with any other innovative technology, the societal implications of drone use need to be investigated, such as occurrences of societal change, ethical issues, privacy violations, and public acceptance [92];
- Another aspect is safety and security. Safety concepts to not harm bystanders (e.g., in case of drone failure, air drones crashing overhead, or delivery bots running into people or vehicles) and security concepts to avoid theft and sabotage by SUGVs and security attacks, e.g., information leakage by UAVs [93,94] will need to be developed and tested;
- The appearance of air drones and delivery bots will also require lawmakers to come up with additional legal regulations on traffic rules, safety, and security aspects as well as damage liability. For delivery bots, these additional regulations can be seen as a subset of the rules to come for automated driving;
- Finally, the scientific operations research (OR) community will have to come up with enhanced or new OR problem models and algorithms to optimize emerging new

delivery concepts that (partly) employ UAVs and SUGVs for last mile home delivery. This OR-focused research is ongoing. Ref. [95], for instance, provided an overview of drone-related emerging OR problem models in their "Table 1. An overview of some relevant works from the literature on drone delivery systems". We assume that the expansion of today's OR modeling scope will continue, especially if the UAV perspective is generalized to also include SUGVs.

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Glossary

CPP	Cost Per kg Payload
CPS	Cost Per Shipment
CVS	Consumer Value Stores (a drugstore company)
dB	Decibel
DHL	a German postal company
Drone delivery	Delivery via UAVs or SUGVs
Drones	UAVs or SUGVs
DRU	Domino's Robotic Unit (drone type)
FAA	Federal Aviation Administration
HW	Heavy Weight
KPI	Key Performance Indicator
LW	Light Weight
M2	Matternet M2 (drone type)
OR	Operations Research
R2D	Robot to Depot
R2T	Robot to Truck
SUGVs	Sidewalk Unmanned Ground Vehicles
TSP-DS	Travelling Salesman Problem with Drone Stations
UAVs	Unmanned Aerial Vehicles
UPS	an American postal company

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