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A R T I C L E I N F O

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A B S T R A C T

Driven by rising consumer demand, interest is growing in the application of autonomous unmanned aerial vehicles (drones) for the last-mile delivery of small express packages and fast-food meals in cities. To be realised, this would require the Very Low Level (VLL) urban airspace to be able to cope with high traffic densities of commercial delivery drones. The potential benefits of such novel drone-based applications are a reduction of traffic congestion in cities, lower greenhouse gas emissions and more efficient transportation operations. To help realise this concept, programs such as U-Space, the unmanned traffic management system for Europe, are developing important services such as deconfliction management and dynamic capacity management. However, for several of these services, design choices will depend on how, and how extensive they will be used. It therefore becomes important to estimate how many delivery drones would operate in a typical city. This paper aims to provide an estimate by establishing a framework to determine the traffic demand for express drone-based package delivery of five European countries. In addition, a detailed case-study is presented for determining traffic density of express package drone delivery for Paris metropolitan area in order to assess the feasibility from a user's perspective. The paper also discusses the potential of fast-food meal delivery drones compared to traditional delivery modes for Paris. Results suggest that hourly traffic densities culminating from express package and fast-food meal delivery drones will exceed today's global commercial aircraft traffic of 10,000 per day by more than six-fold for just one potential metropolitan city.

1. Introduction

Rapid technological advancement of unmanned aerial vehicles, commonly referred to as drones, together with growing consumer demand, have sparked interest in the use of such vehicles in a variety of applications. For example, companies such as Amazon (Pierce, 2013), Jingdong (Russell, 2019) and UPS (Hawkins, 2019) are investigating drone-based delivery of small packages for the last-mile segment (i.e., the segment between the distribution centre and final destination) in urban environments. Also fast-food restaurants such as McDonald's (Technology Review, 2019) and Domino's (Pepitone, 2013), are investigating drones to deliver fast-food meals in dense urban settings.

One of the reasons for this growing interest is the saturation of ground transportation means in dense cities. The population growth of major cities is increasing at a rapid pace (PWC, 2018) which places enormous stresses on the transportation network in order to meet the demands of urban inhabitants (ADB, 2018). This results in transportation gridlocks that have economic (Economist, 2018) and environmental implications (Stolaroff et al., 2018).

Last-mile delivery is considered to be a choke point for the delivery of packages to consumers, especially for e-commerce companies (Economist, 2019). This final segment of the supply-chain accumulates the largest costs, stemming primarily from transport and labour costs (Joerss et al., 2016). It is estimated that the last-mile delivery expends the global parcel delivery industry almost $85 billion per year (Joerss et al., 2016). This corroborates the reason why Amazon and UPS are investigating drone deliveries in urban areas as a viable solution. However when this materialises, the Very Low Level (VLL) urban airspace (i.e. , the portion of the airspace assigned for drones by regulatory bodies) will experience high densities of drone traffic flying in close proximity to natural and man-made obstacles. To explore these commercial demands, Unmanned Traffic Management (UTM) programs such as U-Space in Europe, are developing critical services such as deconfliction management and dynamic capacity management (SESAR-JU, 2017).

An outlook study by SESAR estimated 70,000 delivery drones for

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Europe by 2035 (SESAR, 2016). Other studies discuss possible drone-based delivery traffic densities, focusing on small cities in the US (Narkus-Kramer, 2017). Research has also been done for determining the optimal placement of distribution centres for drone deliveries in European cities (Aurambout et al., 2019).

However, there is no established method for estimating the traffic densities resulting from drone-based delivery for typical European cities. As a result, operational solutions that deal with where, how and when to fly high densities of delivery drones in VLL urban airspace, may have limitations concerning safety and capacity.

The goals of this paper are threefold. In this paper we aim to develop an understanding for estimating the traffic density of parcel delivery drones for a typical dense European city. In addition, we aim to provide a reality check to the feasibility of one application: fast-food meal order delivery via a fleet of drones for a European city. Lastly, we highlight the resulting challenges for U-Space in unlocking the potential for high-density drone traffic in VLL urban airspace.

A selection of the work presented in this paper is an extension of the research originally reported in (Doole et al., 2018) by the same authors. The current paper contributes to this study by updating the statistics of drone-based parcel volumes, improving the overall analysis of the study and, by providing a reflection of key challenges that need to be addressed in future U-Space research studies.

The research in this paper is organised in sections. Section 2 outlines the fundamental assumptions employed for the parcel demand and traffic density calculations. Section 3 lays out an overview of the estimation framework utilised in this study. It then uses this framework to estimate the drone-based parcel delivery demand for five European countries: Germany, UK, France, The Netherlands and Belgium. The section presents a forecast of the drone-based parcel delivery demand for the years between 2035 and 2050 for each country. In addition, the section discusses a case-study of drone-based traffic density numbers for Paris metropolitan area. Section 4 presents a reality check on fast-food delivery via a fleet of drones and it establishes the traffic density for this transport mode. Section 5 presents important challenges that need to be addressed by U-Space in order for drone-based delivery to materialise. Finally, section 6 recaps the key ideas of the paper and presents avenues for future research.

2. Assumptions

The performed analysis to identify the potential demand of drone-based delivery of packages and its resulting traffic density in this study is based on the following set of assumptions:

1. In order to avoid cross-border complications, only domestic (national) parcels are considered. According to global courier company UPS, 85 percent of parcels are delivered domestically, and the remaining 15 percent are internationally-bound parcels (UPS, 2017). Hence, this assumption can be incorporated into this study in order to exclude parcels with international destinations.
2. Only deliveries within an urban area are eligible for drone-based delivery. This is because the focus of the current paper is on understanding the drone-based delivery traffic in an urban airspace.
3. Only a proportion of parcels are suitable for drone delivery since not all parcel deliveries are economically viable to be transported by drones. A previous drone-based parcel delivery estimation study assumed only 70 percent of urban parcel deliveries eligible for drone delivery (Narkus-Kramer, 2017). According to the latter study, the remaining 30 percent represent deliveries where the volume of delivery to a particular area is so high that it becomes more economical to employ traditional transport modes such as trucks or vans.
4. Parcels weighing less than or equal to 2.2 kg are delivered by drones. This is needed to keep the operating cost low (D'Andrea, 2014). More importantly, 86 percent of E-commerce orders from Amazon adhere to this weight constraint.
5. Only the last-mile segment of the delivery is considered in this study since it is the most promising segment for delivery drones (D'Andrea, 2014; Joerss et al., 2016; Economist, 2017; Economist, 2017; and Stolaroff et al., 2018).
6. In this study a drone-based delivery takes an average of 30-min in total to deliver a single package per trip (i.e., 30-min for a single drone to fly to the destination, to deliver the package and for it to return to base). However, it is plausible that this assumption of one parcel delivery by a single drone will change in the future with improved drone technology, which would allow delivery of multiple parcels per delivery trip.
7. The number of operational days for drone delivery is highly dependent on meteorological conditions such as wind speed and precipitation. The drone model employed in this study is capable of operating up to a maximum wind speed of 8 m/s and cannot fly during precipitation (DJI, 2020). According to (Meteoblue, 2020) a typical European urban city such as Paris experiences, on average, winds exceeding 8 m/s as well as some precipitation for approximately 20 percent of the days per year. In this study, we take a conservative assumption of 20 percent to represent no-fly days per year. While the remaining 80 percent represents guaranteed can-fly days. However, with technology development, we expect the proportion of no-fly days owning to weather effects to become minimal in the future.

3. Demand prediction for parcel delivery drones

This section demonstrates the approach to estimate the traffic density of parcel delivery drones. The methodology followed in this study is illustrated in Fig. 1. For this analysis, the parcel numbers for five European countries, that we deemed interesting, were employed. The parcel numbers for the five states include: Germany, The United Kingdom (UK), France, The Netherlands (NL) and Belgium. After extracting the number of parcels for the latter countries, the relevant assumptions described in Section 2 were applied for each state in order to estimate the viable number of parcels for urban areas. Subsequently, growth factors were used to depict the demand for parcel delivery drones for three variant scenarios. Thereafter, the estimates for France were narrowed to identify the traffic density of parcel delivery drones for Paris metropolitan area. Note that the motivation for selecting Paris was to make the results of this study comparable to past research (such as Airbus UTM, 2018).

3.1. Existing delivery parcel volumes

In 2017, 74.4 billion parcels were delivered worldwide. According to a report published by Pitney Bowes, this number was primarily driven by the strong growth of e-commerce giants such as Amazon and Alibaba (Pitney Bowes, 2017). The 2017 figure was an increase of 17 percent compared to 2016 (CEP-Research, 2018; Pitney Bowes, 2018) and it is expected to surpass 100 billion in 2020 (Pitney Bowes, 2018).

According to (Pitney Bowes, 2017), Germany, UK, and France recorded parcel delivery volumes of 3.4, 3.2 and 1.2 billion in 2017, which accounted for an average increase of 6 percent relative to 2016. Similarly, The Netherlands had 350 million delivery parcels in 2016 which was an increase of 12 percent compared to the 2015 numbers (ACM, 2017). Assuming a slightly higher growth of 15 percent for the year 2017, equates to 402.5 million delivery parcels for the Netherlands. Lastly, the Belgium Post (the national postal agency for Belgium) reported to have handled 190,000 parcels on a daily basis in 2017 (Bpost, 2017). This amounts to approximately 69.4 million delivery parcels in Belgium for 2017.

In order to estimate the above parcel delivery numbers for 2019, for the respective countries, it is assumed that all five countries experienced an average growth rate of 8 percent (from 2017 to 2019) yearly (Pitney Bowes, 2018). This forecast is presented in Table 1. The estimates in

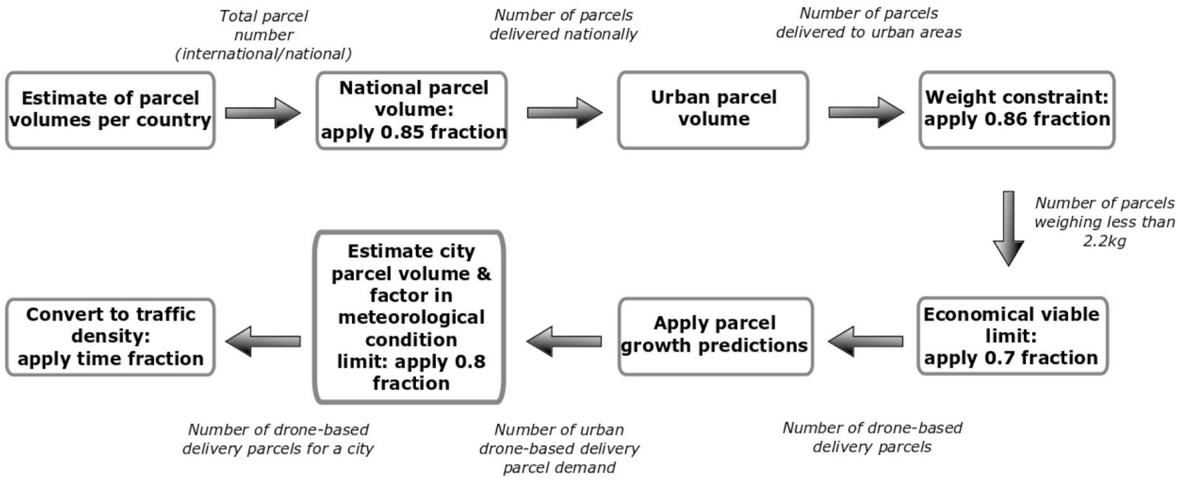

Fig. 1. Framework diagram to estimate the traffic density of drone-based delivery parcels in an urban airspace.

Table 1 include both national and international delivery parcels. Since this study investigates the demand for drone delivery per country, internationally-bound delivery parcels are excluded and focus was given to domestic parcels which are eligible for drone delivery. According to global courier company UPS, 85 percent of delivery parcels comprise of domestic bound parcels in the US (UPS, 2017). Assuming the same holds true for the five European countries in this study, results in domestic parcel delivery numbers (see Table 2).

3.2. Number of parcels delivered to urban areas

In 2018 the World Bank (World Bank, 2019a) estimated that approximately 77 percent of the Germany's population reside in urban areas. Similarly, in the UK, 83 percent of the population are concentrated in urban environments. France has 80 percent of its inhabitants in urban cities while the Netherlands and Belgium holds 91 and 98 percent of their population in urban areas, respectively. These percentages have remained constant since 2016 and therefore, it can be assumed that the fraction of the population living in urban areas remains the same through 2019 (World Bank, 2019a). By factoring the urban population percentages to the number of national delivery parcels given in Table 2, equates to the number of parcels delivered to urban areas for each of the five countries (Table 3). Note that this is a conservative estimate, as the per-capita demand in urban areas is often larger than, not equal to the demand for e-commerce in rural areas (Harrington, 2019).

3.3. Number of urban delivery parcels less than or equal to 2.2 kg

The above parcel numbers comprise of parcels with weights up to 31.5 kg (Pitney Bowes, 2017). Several drone delivery companies such as Amazon Prime Air, Matternet and Flirty have focused design efforts on transporting 2.2 kg over a distance of 10 km, which according to (D'Andrea, 2014) is the optimal design requirement with respect to operating costs. According to Amazon, 86 percent of parcels delivered are below 2.2 kg (Pierce, 2013). Since the demand for delivery parcels are primarily driven by the growth in e-commerce, it is a reasonable design requirement for the urban airspace to accommodate such realistic traffic densities. Taking into account the 86 percent factor, results in the number of delivery parcels eligible for drone transport for the five European states (Table 4). Note that economic and technical developments could increase the maximum weight at which packages are (economically and technically) feasible to be transported by drone. In this case the 86 percent fraction used in this paper is a conservative estimate.

Table 1
Expected number of delivery parcels for five European countries in 2019.

	Germany	UK	France	NL	Belgium
No. of delivery parcels	4.0 billion	3.7 billion	1.4 billion	469.8 million	81 million

Table 2
Expected number of domestic/national delivery parcels for five European countries in 2019.

	Germany	UK	France	NL	Belgium
No. of delivery parcels	3.4 billion	3.14 billion	1.19 billion	399.3 million	68.8 million

Table 3
Expected number of delivery parcels to urban areas for the five European countries in 2019.

	Germany	UK	France	NL	Belgium
No. of delivery parcels	2.61 billion	2.6 billion	952 million	363.4 million	67.4 million

3.4. Number of parcels eligible for drone delivery

The economic advantages for employing drones in-place of traditional transport modes (trucks and vans) for last-mile delivery have been demonstrated in several studies (D'Andrea, 2014; Joerss et al., 2016; Economist, 2017; Economist, 2017; and Stolaroff et al., 2018). The last-mile is defined as the segment between the distribution centre and the final destination. It is assumed that only for 70 percent of the urban packages, drone delivery will be economically viable (Narkus-Kramer, 2017). The remaining 30 percent are package deliveries in areas where the volume of delivery is so high that it becomes more economical to employ traditional transport modes such as trucks or vans. The values in Table 4 should therefore be multiplied by a factor of 0.7, resulting in a set of estimates for drone-enabled delivery parcels in urban areas for the five countries for 2019, shown in Table 5.

Table 4
Expected number of delivery parcels to urban areas that satisfy the weight limit of 2.2 kg for the five European countries in 2019.

	Germany	UK	France	NL	Belgium
No. of delivery parcels	2.24 billion	2.23 billion	818.7 million	312.5 million	58 million

3.5. Future growth in the number of delivery parcels by drones

The SESAR U-Space outlook study postulates delivery drone services to be viable by 2035 (SESAR, 2016). In order to be synchronised with the SESAR U-Space program, we perform a forecast to estimate the number of drone-eligible parcel deliveries for the five European countries until 2050. To be conservative with the drone-based parcel delivery demand forecast, the average economic growth rate is used, which stands at 1.8 percent for Europe as of 2019 (CBS, 2019). If we assume the demand for drone-based delivery to be aligned to the average economic growth rate for the next 30 years for the five countries, three different scenarios (low, medium and high) can be explored in this study. In a low growth scenario, we assume the economic growth to be half of 1.8 percent (i.e., 0.9 percent) per year for the next 30 years. While for the medium growth scenario, we assume that the current 1.8 percent to represent the average growth until 2050. Under the high growth scenario, we consider the yearly growth rate to be twice of 1.8 percent (i.e., 3.6 percent per year). The extrapolated results in annual drone parcel delivery numbers for each of the five countries, from the baseline year 2019–2050, is presented in Fig. 2.

3.6. Estimate for the traffic density of parcel delivery drones in Paris

The Paris metropolitan encompasses approximately 12.5 million people within an area of 12,012 km^2 (Insee, 2018). Taking into account a 0.5 percent growth since 2015 (Insee, 2018), amounts to 13.1 million inhabitants in the Paris urban area for 2019. This figure represents 24 percent of the total urban population (54 million) of France (World Bank, 2019b). This 24 percent was incorporated into the values represented for France in Fig. 2 in order to obtain estimates for the annual number of drone-eligible delivery parcels in Paris, as presented in Table 6.

With the assumption that drone deliveries only take place 80 percent of the days per year due to favourable meteorological conditions (see assumption 7 of Section 2), within an 8-h operating time-window (based on the average hourly work-day schedule), the hourly demand for parcel deliveries by drones is computed for Paris (Table 7). The drone delivery traffic movements for the realistic scenario (which postulates a 1.8 percent growth in parcel delivery demand), expects a traffic volume of 78,082 flights per hour within the urban airspace of Paris in 2035. According to Amazon, a single delivery drone is able to deliver a parcel over a maximum distance of 10 km within an average flight time of 15 min (Pierce, 2013). In keeping with Amazon's delivery time estimation, it is assumed that a single drone has a total round-trip time (time to deliver and return to home-base) of 30 min, which includes the time to fly to the respective destination, make the delivery to the customer and to return to home-base. As a result, the traffic density of delivery drones is obtained by dividing the traffic movements per hour by a factor of two for the metropolitan area of Paris (Table 8). The traffic numbers represented in Table 8 reflect the potential drone-based parcel delivery urban airspace traffic densities that may arise in the future, provided that safety concerns and societal acceptance have been addressed.

Traffic density is an important metric in airspace design. It can be employed to investigate the safety and capacity of different airspace design concepts. The expected traffic density volumes of aerial vehicles are already significantly higher when compared to the current global commercial aircraft traffic, which record approximately 10,000 flights per hour on average, globally (Flightradar24, 2019). In addition, there have been recent experiments in using drones to deliver fast-food in dense urban environments by companies such as Google Wing, UberEats and Flytrex (McNabb, 2019; Martin, 2019; BBC, 2018). These companies are interested in drone delivery to be able to meet shorter delivery times at lower costs. This means that the demand for drone-based delivery may further increase. When considering that the probability for traffic conflicts grows quadratically with traffic density (Hoekstra, 2001), managing airspace complexity will be one of the main challenges of unmanned traffic management concepts such as U-Space.

Table 5
Expected number of drone-enabled delivery parcels in urban areas for 2019.

	Germany	UK	France	NL	Belgium
No. of delivery parcels	1.57 billion	1.56 billion	573 million	218.7 million	40.6 million

4. Fast-food meal delivery cost comparison between drones and E-bike modes

The online food-delivery industry is growing rapidly, mainly due to higher customer satisfaction levels which is propelled by shorter delivery times (Hirschberg et al., 2016). To cope with this demand, restaurants use third-party logistic providers, or employ couriers, to perform deliveries via electric-bicycles (E-bikes). Despite such food-delivery options being ubiquitous in cities, there are disadvantages. For example, delivery via E-bikes present a safety hazard to pedestrians and other road-users in cities (Schepers, 2014; Surico, 2018) and the cost of labour erodes profit margins (Keng, 2018). E-bikes may also become affected by traffic congestion thus creating delays to delivery schedules (Surico, 2018). Because of this, several companies have performed field tests on novel transport modes such as drones for food-delivery tasks. Recent studies have investigated different food-delivery dispatch algorithms for drones (Liu, 2019) and also, studies have been done in understanding customer behaviour towards drone food-delivery (Hwang et al., 2019). However, little is known about the economic feasibility and the resulting traffic densities for drone delivery of fast-food meals in dense urban areas.

This section explores the costs associated to operating drone food-delivery for a cluster of fast-food restaurants in Paris metropolitan area. The costs are compared to the existing logistics mode of E-bikes. An estimate is obtained for the traffic density arising from drone food-delivery in order to determine the overall delivery drone numbers for Paris. Therefore for this case-study, a comparison is made between the DJI Matrice 600 Pro (a hexa-copter drone modified for food-delivery) and traditional E-bikes (battery-assisted bicycles) in food-delivery (Fig. 3).

4.1. Estimating the number of drones and E-bikes

According to (the Local, 2019), the quick-service restaurant chain McDonald's, in France, served 1.8 million meals per day across its 1464 restaurant stores in 2019. A study in 2012 by (NPD Group, 2012) estimated that approximately 57 percent of meals sold at hamburger restaurants, such as McDonald's, represented take-out/delivery meals. Given a 3.5 percent growth in food-delivery meals per year from 2012 to 2019 (Hirschberg et al., 2016) results in 72.5 percent of the proportion of meals being delivery meals. Of note, this fraction of delivery meals is also aligned with the recent trends in online food delivery, suggesting that delivery meals are increasingly more popular than dine-in meal orders (Morgan Stanley, 2017). As a result, the number of delivery meal orders per day amounts to 1.3 million across the 1464 restaurants. In our model we use McDonald's as a potential case-study restaurant due to the general availability of data and its interest to employ drones for food delivery in the future (Technology Review, 2019). Given these statistics, we can estimate the number of meal deliveries per hour per restaurant kitchen. Assuming a uniform distribution of meals per day in all restaurants, this equates to approximately 888 meals per day per restaurant kitchen. According to (Uber Help, 2020), typical restaurants serve the greatest demand within a 7-h time-window per day (i.e., between lunch time from 11:00 to 14:00 and between dinner time from 17:00 to 21:00). Furthermore, we assume that the latter demand is evenly spread across the 7-h period. As a result, the number of meal orders per hour per kitchen amounts to approximately 127. Of note, the latter number of

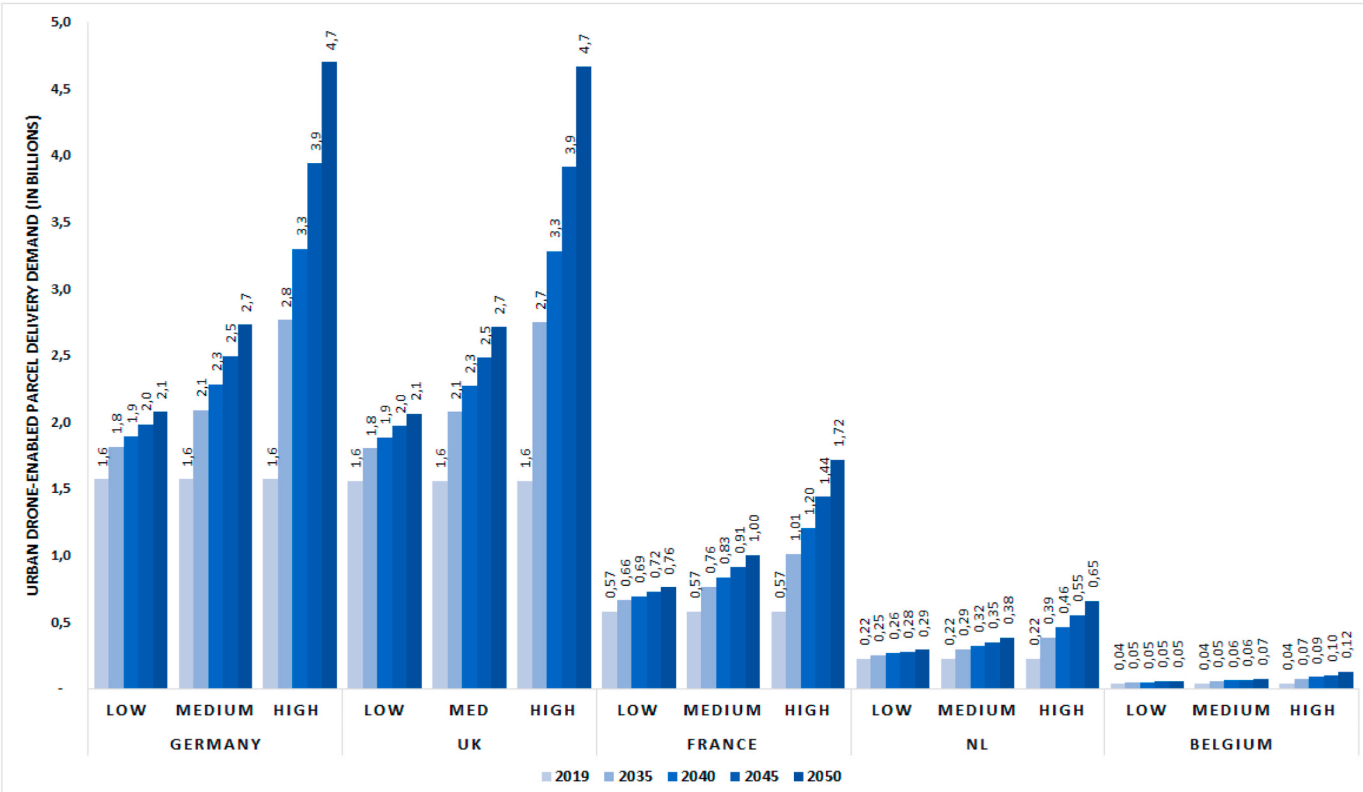

Fig. 2. Urban drone-enabled parcel delivery demand for three variant scenarios of 0.9, 1.8 and 3.6 percent average yearly growth rates until 2050. Of note, theqq year 2019 is the baseline year for the extrapolation.

Table 6
Expected number of eligible parcels for drone delivery in the Paris metropolitan area per year for 2035–2050.

Year	Low	Medium	High
2035	158.4 million	182.4 million	242.4 million
2040	165.6 million	199.2 million	288 million
2045	172.8 million	218.4 million	345.6 million
2050	182.4 million	240 million	412.8 million

Table 7
Expected number of parcel delivery drone movements (drone flight traffic volume per hour) in the Paris metropolitan area for three variant scenarios.

Year	Low	Medium	High
2035	67,808	78,082	103,767
2040	70,890	85,274	123,288
2045	73,973	93,493	147,945
2050	78,082	102,740	176,712

Table 8
Expected traffic density of parcel delivery drones in the Paris metropolitan area for three variant scenarios.

Year	Low	Medium	High
2035	33,904	39,041	51,884
2040	35,445	42,637	61,644
2045	36,987	46,747	73,923
2050	39,041	51,370	88,356

meal orders per hour per kitchen is assumed as the best case scenario in terms of frequency. Due to the lack of data, for the analysis, the number of McDonald's restaurants situated in Paris metropolitan area was obtained from OpenStreetMap data. The data generated from OpenStreetMap resulted in 291 restaurants belonging to the McDonald's fast-food chain within the specified area (see supplementary information appendix 1). From the estimated 888 meals per day per restaurant kitchen, the total number of potential meal delivery orders for Paris metropolitan sums to 258,408, which results to roughly 36,915 meal orders per hour.

Similar to the assumptions employed in section 3, we assume a drone takes 30 min on average to deliver a single order to one customer (see assumption 6 of Section 2) and return back to one of the 291 restaurant kitchens. This results in 18,458 food-delivery drones as presented in Equation (1). To match the previously-mentioned hourly delivery demand rate for the 291 kitchens, it is assumed that the total number of delivery drones are uniformly distributed among the 291 kitchens.

$$\textit{Number of delivery drones} = \frac{36,915 \text{ meal order}}{1 \text{ hr}} \times \frac{1 \text{ drone}}{2 \text{ meal orders/hr}} = 18,458 \textit{ delivery drones} \tag{1}$$

$$\textit{Number of delivery Ebikes} = \frac{36,915 \text{ meal order}}{1 \text{ hr}} \times \frac{1 \text{ E bike}}{5 \text{ meal orders/hr}} = 7,383 \textit{ delivery E bikes} \tag{2}$$

In the case of E-bikes, the capacity of a cargo-box is used to estimate the number of meals that can be delivered per hour per trip. According to (eBike4delivery, 2020), a food-carrying cargo-box has an estimated capacity to carry five large pizzas/large meals. Therefore, in this study it is assumed that an E-bike can transport five meals per hour to five independent customers. Taking into account the hourly meal order rate, 36,915 orders per hour, this results in 7383 E-bikes (illustrated in Equation (2)) to meet the demand. Furthermore, the total hourly meal order demand is uniformly distributed across the 291 kitchens. This means that all 291 restaurants will require 7383 E-bike couriers to

Fig. 3. Example of a fast-food delivery hexa-copter drone, adapted from (Krader, 2019); and a typical fast-food delivery E-bike with an integrated delivery cargo box, adapted from (Toll, 2019).

operate and handle the delivery of hourly meal orders.

In order to estimate the cost of delivering fast-food via the two transport modes, three variant scenarios are employed. The scenarios include: conservative, high potential and high acceptance. Note that the scenario names used are based on the SESAR Outlook study (SESAR, 2016). Scenario 1, which assumes a conservative scenario case foresees a future of harmonised legislation hence permitting Beyond-Visual-Line-Of-Sight flights post 2020 and social concerns that limit urban delivery in specific regions of cities. Scenario 2, high potential, predicts a future where multiple large-scale delivery service providers integrate drone delivery to their delivery fleet and drone-based delivery gradually begins to accelerate demand. Scenario 3, which assumes higher acceptance scenario case, forecast a scenario where there is a rapid growth in technology, such as fully autonomous flights thus improving safety and, decrease of costs due to economies of scale. Each of these scenarios will be compared against cost variables for each transport mode. Ultimately, the costs will be compared to the traditional electric-bicycle delivery mode.

Table 9
Drone-based food-delivery costs estimation for pessimistic, realistic and optimistic scenarios.

Delivery drone			
Parameter	Conservative	High potential	High acceptability
Number of drones	18,458	18,458	18,458
Cost of drone (€)	5699	4274	2850
Cost of modification per drone (€)	150	100	0
Cost of extra battery (€)	899	450	225
Annual maintenance cost per drone (€)	1710	427	142
Annual liability insurance cost per drone (€)	1000	500	100
Total investment cost (€)	174,567,524	106,153,545	61,291,162
Depreciation time (years)	7	7	7
Annual investment cost (€)	24,938,218	15,164,792	8,745,595
Number of operational days	292	292	292
Daily investment cost (fixed cost) (€)	85,405	51,934	29,951
Airspace cost per drone (€/hr)	2	0:50	0:25
Labour cost (€/hr)	30	20	20
Number of operators	1455	582	291
Number of operational hours per day	7	7	7
Daily operational cost (€)	563,958	146,082	73,041
Total daily cost (€)	649,363	198,016	102,992
Delivery cost per meal order (€)	2.51	0.77	0.40

4.2. Delivery drone cost variables

This section presents the cost variables that are employed to estimate the cost of delivering a fast-food meal order using a fleet of drones.

4.2.1. Cost of drone

The cost of the drone (i.e., DJI Matrice 600 Pro) for the conservative scenario was obtained from a manufacturer's cost estimate (DJI, 2019). This cost estimate is priced at €5699 per unit and it is far higher than its competitors. This price-point can be considered to be a conservative case and hence why it is used in the conservative scenario. For the high potential case, the cost of a drone is assumed to be 75 percent of the conservative scenario cost while in the high acceptability scenario the cost of the aerial vehicle is assumed to be 50 percent of this cost estimate. This reduction in the cost of a drone can be reasoned by the future decrease in the sensor technology costs. The cost decrease of drones could mimic the sharp decrease of prices for mid-range smartphones (Belton, 2015).

4.2.2. Cost of modification

Modification is required to equip the drone with a payload-carrying capability i.e., a lightweight payload hull to house the fast-food meal order. In the conservative scenario, it is assumed that the modification cost is borne by the client. Realistically, the manufacturer could charge a reasonable price for modifications. As the demand increases, we assume that the economies of scale will help reduce the cost of modification to zero. This can be seen in the high acceptability scenario (see Table 9).

4.2.3. Cost of battery

The drone battery is recharged at the respective restaurant at which the drone is stationed at. In order to ensure uninterrupted service, the drained battery, from the respective drone, is unloaded for it to be recharged at a charging station. Subsequently, a fully-charged battery is loaded onto the drone. As a result, each drone will require an additional battery, hence incurring a cost. The price of lithium-ion batteries is likely continue to decrease yearly (Chediak, 2017; Berckmans et al., 2017). A recent analysis estimated the average selling price of lithium-ion battery packs to be €175/kWh which is a 24 percent decrease since 2016 and 79 percent decrease since 2010 (Chediak, 2017). By 2025 the price of a lithium-ion battery pack is projected to decrease to €84/kWh (Chediak, 2017; Berckmans et al., 2017). The manufacturer's (DJI, 2019) cost estimate for an extra drone battery is priced higher compared to its competitors. Therefore, the cost of an extra battery, seen in the conservative scenario, is taken from the manufacturer's cost estimate. And, in a high potential scenario, the cost of the manufacturer's drone battery is estimated to decrease by 50 percent to match the competitor price-point. Similarly, in the high acceptability scenario, we assume the cost of the battery to decrease by 75 percent in the future, as predicted by (Tsiropoulos et al., 2018).

4.2.4. Annual maintenance cost per drone

The need for maintenance will decrease with the evolution of drone technology. Currently, the maintenance cost is assumed to be 30 percent of the cost of the vehicle for the conservative scenario. This is a relatively high cost for maintenance and as the cost of the vehicle decreases together with further advancement in technology, the cost of maintenance will decrease. The high potential scenario is expected to reduce the annual cost of maintenance to 10 percent of the cost of the vehicle and 5 percent of the cost of the drone for the high acceptability scenario.

4.2.5. Annual liability insurance cost per drone

The liability insurance cost for delivery drones is still not well defined due to its novelty. According to (Leonard, 2019), the cost for the annual liability insurance for consumer drones ranges between €600 to €1600 per drone. We believe that as drones become increasingly intelligent, and as U-Space unfolds to become a matured ecosystem for drones, the cost of annual insurance will decrease. According to (Travers and Associates, 2018), the cost of insurance for drones is predicted to decrease due to competitive pricing as more insurance providers enter the market. Therefore, based on the above reasons we can estimate the cost for the yearly liability insurance for a delivery drone. Hence, we assume for a conservative case, the cost of insurance to be €1000 while for the high potential case the price should be €500 and, more optimistically, €100 per year for the high acceptability scenario.

4.2.6. Number of drone operators

The number of operators for operating/piloting (i.e., flight planning, monitoring and tracking, servicing etc.) of delivery drones is assumed to be dependent on the level of autonomy. Loading food parcels (unloading is assumed to be done by the recipient/customer at the delivery destination location) and handling the delivery drone, i.e., packaging and loading of food, is assumed to be performed by existing restaurant employees thus warranting for no specialised personnel to handle and load food parcels. This is likely to be similar to how existing quick-service restaurants employees operate online food-delivery applications, supplied by Uber Eats or Deliveroo, with minimum training and no additional salary increment. The conservative and high potential scenario is assumed to require more than one operator. In particular, the number of drone operators for the conservative scenario is five operators per kitchen, hence resulting in 1455 operators in total. For the high potential scenario, it is assumed that progress in drone technology will increase its ease of use and the level of autonomy, thus reducing the number to two operators per kitchen, which equates to 582 operators in total. Similarly, the high acceptability scenario assumes to have full autonomy hence, this scenario will not require many operators. As a result, only a single operator is assumed to be stationed for each kitchen, which amounts to 291 operators.

4.2.7. Labour cost per hour

This cost is attributed to employing drone operators. The labour cost is assumed to reduce with increasing level of autonomy. According to (Payscale, 2020), the average cost of labour per hour for a drone operator in the US can vary roughly between €15 and €50. Assuming an equal pay-scale in France, we use €30 (rounded average of the latter lower and upper hourly labour costs) as the hourly cost of labour for the conservative scenario as a consequence of high demand and skill of labour needed to manually, or semi-automatically, operate a drone in a complex urban environment. Similarly, as the operational use of delivery drones reduce in complexity with the supply of full autonomy, which might only require entering of the recipients address, the cost of labour will decrease. For this reason, the cost of labour for the high potential and high acceptability scenario is assumed to decrease to €20 per hour.

4.2.8. Airspace cost per drone per hour

The cost of utilising the airspace can be viewed as a measure to control congestion in addition to making UTM/U-Space a profitable business. Hence there will always be a cost for using the airspace. However, UTM and U-Space have yet to establish such unit economics. As a result, the airspace utilisation cost will need to be assumed for this analysis. For the conservative scenario, a cost of €2 per hour per drone is assumed. For the high potential and high acceptability cases, the cost for airspace is assumed to decrease and represent €0.50 and €0.25. This is assumed to take place as U-Space unfolds progressively with time.

4.2.9. Number of operational days

Due to meteorological conditions such as high winds and precipitation, not all drone fights will be guaranteed all-year round. A proportion of the drone-based delivery flights will experience no-fly days. Based on such data, we take a conservative assumption of 20 percent to represent no-fly days per year for our study (see assumption 7 of Section 2). This assumption is applied across all three scenarios in Table 9. However, note that as technology advances we expect a decrease in the proportion of no-fly days per year, especially during mild precipitation periods.

4.3. Delivery E-bike cost variables

This section presents the cost variables that are used to compute the delivery cost of a meal order via E-bikes.

4.3.1. Cost of E-bike

This cost is given by the manufacturer's catalogue in (eBike4delivery, 2018). The manufacturer's cost estimate is used for the high potential scenario. Depending on the external factors such as tax initiatives, the cost of an E-bike in a conservative scenario is assumed to be €2500 per bike. Similarly, in high potential and high acceptability scenarios, the cost of the E-bike is assumed to decrease by 25 and 40 percent respectively lower due to factors such as tax incentives, economies of scale and competitive pricing.

4.3.2. Cost of modification

This involves costs associated to integrating the E-bike with a special food transport box in order to keep the meals warm. An average size box cost approximately €150 according to (eBike4delivery, 2018). This is assumed to be the cost for the conservative case. For the high potential case and high acceptability case, the costs is assumed to be €100 and €50.

4.3.3. Cost of battery

To enable uninterrupted food-delivery, each E-bike is assumed to have an extra battery. In the event of a drained battery, it can be unloaded and a fully-charged battery can be loaded at the respective restaurant at which the E-bike is stationed at. Similar to the delivery drone, the cost of lithium-ion batteries is assumed to decrease by 50 and 75 percent respective to the conservative price scenario which was derived from the manufacturer's catalogue (eBike4delivery, 2018).

4.3.4. Annual maintenance cost per E-bike

This cost factor is based on the usage of the bike. Estimates for maintenance cost for an E-bike is obtained from (EBR, 2018a) in which a range is specified for maintenance cost estimates between €180 - €105 per year. The highest cost from the range is employed for the conservative scenario which stands at €180 per year. Then, the average of the range, €142, is assumed for the high potential scenario. And finally, for the high acceptability scenario, the lowest cost of the maintenance cost range is assumed at €105 per year.

4.3.5. Annual insurance cost per E-bike

The cost of insurance for theft and damage for E-bicycles are relatively low compared to drones. According to (EBR, 2018b), insurance cost per E-bike can vary from €33 - €84 per year. For this study we assume the insurance cost for the conservative scenario to be €84 i.e., we assume the highest value from the above range. The average of the range (€58.5) is employed for the high potential scenario and the lowest value from the range, €33, is assumed to hold true in the high acceptability case.

4.3.6. Labour cost per hour

This cost is mainly driven by the cost of employing couriers for operating the E-bikes and in delivering meal orders, which can be highly labour intensive. Quick-service restaurants generally employ delivery personnel between the ages of 16 and 17 years. This is evident in Europe.

As a result, the cost of labour is relatively cheap since employers are not stipulated to meet the minimum wage threshold (WageIndicator, 2019). We assume that the cost of labour for couriers to remain steady at €10 per hour for all three scenarios.

4.4. Comparison between drone and E-bike delivery of fast-food meals

The feasibility of delivering fast-food meals for 291 restaurant kitchens in Paris by a fleet of drones or E-bikes has been analysed for three different scenarios. Table 9 illustrates the different costs associated with delivering meal orders using a fleet of 18,458 drones to meet the hourly demand of 36,915 meal orders for the three scenarios. Based on these different costs, and the total fast-food demand of 258,408 meal orders per day, the delivery cost per individual meal order via a drone is presented (Table 9). For the conservative scenario, this delivery cost amounts to €2.51 per meal order. In the high potential case, the cost of delivery by drone is €0.77 per meal order. This is similar to the cost reported in (Keeney, 2015), albeit for a small consumer package, which estimated the delivery cost to be approximately €0.79 per order via a drone.

In the high acceptability scenario, the drone-based delivery cost is estimated to be €0.40 per meal order. Compared to the conservative scenario, the high potential and high acceptability scenarios indicate a significant decrease in delivery cost. This is primarily attributed to the lower number of required drone operators due to the assumption of autonomous drone operations, which is expected to be viable as technology progresses.

Table 10 illustrates the E-bike food-delivery costs for the three scenarios. In comparison to drone delivery, the annual investment cost for E-bike delivery is relatively low due to the lower cost of the E-bike. However, this benefit is outweighed by the daily operational cost that is caused as a result of labour intensive delivery trips. Unlike drones, E-bikes (or any road-based vehicle) are difficult to automate due to the high complexity of the ground-based environment, and the presence of high numbers of unpredictable dynamic obstacles. As a consequence, large numbers of fully automated aerial vehicles are sooner expected to be viable than large numbers of fully automated ground-based vehicles.

As seen in Table 10, wages paid to the (7,383) couriers represent the largest portion in the total daily operational expense. Since a conservative assumption is made for steady wages across all three scenarios, the delivery cost per meal order does not decrease across the three scenarios. For all three scenarios the E-bike food-delivery cost is between €2.03 and €2.02 per meal order. This cost range is in line with average delivery cost per order for large-scale quick-service restaurant chains (Nichols, 2013).

Table 10
E-bike food-delivery costs estimations for pessimistic, realistic and optimistic scenarios.

Delivery E-bike			
Parameter	Conservative	High potential	High acceptability
Number of E-bikes	7383	7383	7383
Cost of E-bike (€)	2500	1875	1500
Cost of modification per E-bike (€)	150	100	50
Cost of extra battery (€)	100	50	25
Annual maintenance cost per E-bike (€)	180	143	105
Annual insurance cost per E-bike (€)	84	59	33
Total investment cost (€)	22,252,620	16,434,749	12,647,226
Depreciation time (years)	7	7	7
Annual investment cost (€)	3,178,946	2,347,821	1,806,747
Number of operational days	365	365	365
Daily investment cost (fixed cost) (€)	8709	6432	4950
Labour cost (€/hr)	10	10	10
Number of couriers	7383	7383	7383
Number of operational hours per day	7	7	7
Daily operational cost (€)	516,816	516,816	516,816
Total daily cost (€)	525,525	523,248	521,766
Delivery cost per meal order (€)	2.03	2.02	2.02

The above analysis indicates the potential economic feasibility of using a fleet of autonomous drones to deliver meals from a cluster of McDonald's restaurants in Paris. The cost of operating a fleet of food-delivery E-bikes is nearly twice as more compared to drone-based delivery. As a result, large-scale quick-service restaurants such as McDonald's, could benefit from switching their food-delivery mode to high-speed drone delivery. In addition, the associated cost-savings could be passed onto the consumers, which will likely trigger further demand for the food-delivery service. The use of drone-based delivery may also alleviate some of the road traffic congestion arising from the traditional food-delivery modes. This results to a reduction of 7383 E-bikes from the urban street network thus, increasing the level of safety for road-users.

Research by (Rabobank, 2018) indicate a 11 percent growth per year (between 2017 and 2022) in food-delivery for France. However, it is unlikely that such growth figures can be sustained until 2050. Therefore, we take a conservative estimate by assuming growth-rates of 0.9, 1.8 and 3.6 percent yearly, similar to the average economic growth, in the online food-delivery industry between 2035 and 2050. Hence, a forecast can be made for drone-based traffic density stemming from meal order deliveries for Paris (Table 11). The expected traffic density of drone-based meal orders by 2035 could potentially reach nearly 24,555 drones per hour in an area of 12,012 km^2. Therefore, to make drone-based food delivery viable, infrastructural, technological and legislative bottlenecks will need to be solved.

The physical infrastructure at restaurant kitchens currently supports the integration of E-bikes due to minimum infrastructure requirements. In order to handle fleets of delivery drones, off-site restaurants (see Bradshaw, 2019) that exclusively focus on meal-deliveries, may prove to be more practical to integrate and operate food-delivery drones (Healy, 2019). However, safety concerns such as integrating take-off and landing pads (or docking stations) at restaurants situated in dense urban environments are yet to be investigated. Similarly, the integration of such take-off and landing pads and their associated drone charging stations may also require large financial investments which may not be attractive to quick-service restaurant operators. On the technological and legislative front, this potential can only be realised when the level of autonomy for food-delivery drones becomes matured, or as cognitive autonomy is achieved (Floreano and Wood, 2015), thus requiring a lower number of operators, and when U-Space is fully capable of safely handling high-density drone traffic in VLL urban airspace. A summary of the above comparative analysis between drone delivery and E-bike food-delivery is presented in Table 12.

5. Challenges for U-Space

U-Space is considered to be a key technology enabler for the execution of safe aerial missions such as food and express package

Table 11
Expected traffic density of drone-based meal delivery drones in the Paris metropolitan area, with an area of 12,012 km^2, for three variant scenarios which forecast food-delivery growth at 0.9, 1.8 and 3.6 percent. Note the baseline year is 2019 for which 18,458 food-delivery drones were estimated in an area spanning 12,012 km^2.

Year	Low	Medium	High
2035	21,303	24,555	32, 504
2040	22,279	26,846	38, 791
2045	23,300	29, 351	46, 295
2050	24,367	32, 089	55, 250

Table 12
Summary of comparative analysis for the two transport modes of fast-food meal delivery. We show the main advantages and disadvantages between drone-based delivery and E-bike delivery of fast-food meals which was gathered from the analysis.

Transport mode	Pros	Cons
Delivery drone	• Relatively easier to automate due to lower complexity of environment, and lower number of unpredictable dynamic obstacles. • Able to perform high-volume and high-speed delivery • Helps reduce traffic congestion.	• Requires infrastructure changes for integration. • Delivery cost is dependent on the level of automation. • Requires high investment cost.
Delivery E-bike	• Existing infrastructure supports integration. • Requires low investment cost.	• Delivery cost is highly dependent on cost of labour. • Prone to high number of road accidents when high-speed delivery is required, • Delivery may get affected by traffic congestion. • Difficult to automate due to the presence of high number of unpredictable dynamic obstacles

delivery by drones. The U-Space program (SESAR-JU, 2020) defines four progressive U-Space deployment levels: U1, which is a set foundation services to allow for drone registrations and identification; U2, consist of a set of initial services to enable safe administration and management of drone flights; U3, comprise of advance services to support high-density drone operations in complex environments; and U4, will integrate U-Space with current air traffic management and the capability of full autonomy. A comprehensive list of service for each U-Space deployment level is presented in Table 13.

Each of the U-Space level consists of a set services aimed at supporting and adopting the growth of drone operations for European Union (EU) member states. However, challenges associated with integrating high densities of drone traffic to the urban airspace in a safe and efficient manner, is yet to be tackled by the regulatory and technological apparatus of U-Space.

The question remains what would be the expected volume of drone traffic for a typical urban airspace such as Paris. The study conducted by (Airbus UTM, 2018) estimated an average of 16,667 delivery drones per hour, or a traffic density of 8333 delivery drones, for Paris by 2035. The latter figure is nearly eight-fold lower than the potential scenario of traffic density delivery drones of 63,596 estimated in this study for both express parcel and food deliveries.

The current study gives an estimate of the potential for drone-based transportation based on all eligible deliveries, whereas in practice, adoption of this means of transportation may be more gradual. However, even a fraction of such traffic densities will place challenges for the urban airspace to efficiently accommodate this while maintaining an acceptable level of safety. In addition, the demand for package and fast-food delivery drones is located in dense urban areas which is inundated by several airspace constraints. First being the limitation of drone flights in urban areas to a thin altitude band, known as Very Low Level or VLL airspace which stipulates drones to fly between 0 and 500 ft, above ground level. Second, urban areas are congested by heterogeneous (permanent and non-permanent) man-made and natural obstacles (Petrovsky et al., 2018). For example, Paris city has more than 350,000 man-made permanent obstacles with varying heights, within an area of 105 km^2. Urban areas are also prone to a high number of temporary and permanent No-Fly-Zones that prohibit drone flights over particular locations such as schools, parks, stadiums and government buildings, supported by geofences. The VLL airspace is also occasionally populated by manned flight traffic, for instance general aviation aircraft, gliders and helicopters which further constrain the airspace for urban drone ights.

Table 13
U-Space services in U1, U2, U3, and U4 deployment levels, extracted from (SESAR-JU, 2020).

U-Space deployment level	U-Space service
U1: Foundation services	Registration; Registration assistance; E-Identification; Geo-awareness; Drone aeronautical information management.
U2: Initial services	Tracking; Surveillance data exchange; Geo-fence pro-vision; Operation plan preparation; Operation plan processing; Risk analysis assistance; Strategic conflict resolution; Emergency management; Incident/accident reporting; Citizen reporting service; Monitoring; Traffic information; Weather information; Navigation/communication infrastructure monitoring; Legal recording; Digital logbook; Procedural interface with air traffic control.
U3: Advanced services	Dynamic capacity management; Tactical conflict resolution; Geospatial information service; Population density map; Electromagnetic interference information; Navigation/ Communication coverage information; Collaborative interface with air traffic control.
U4: Full services	Integrated interfaces with air traffic control; Autonomous flight

The expected volumes arising from express parcel and food delivery, combined with the various airspace constraints, presents major challenges for U-Space to optimally integrate high densities of drone traffic to the urban airspace. As high volumes of drone-based delivery missions begin to gradually unfold in the urban airspace, for several low-level (U1, U2) U-Space services, the load will scale linearly with the number of operations (number of registrations, number of information requests). However, since traffic complexity contains a quadratic component of traffic density (through e.g., conflict probability), the demand for high-level U3/U4 services such as dynamic capacity management and tactical conflict resolution will be unparalleled compared to our current situation of controlled airspace, and thus the implementation of such services will require a fundamentally different approach (see Hoekstra et al., 2018). Hence U-Space policymakers and researchers should address such crucial challenges by developing adequate protocols and robust airspace design measures in order to enable safe high-density drone-based delivery missions.

6. Conclusion

Drone-based delivery of small consumer packages and fast-food meals has the potential to make a large contribution to transportation in urban areas. Drones represent an agile and sustainable transport mode for e-commerce companies and quick-service restaurants, especially when high-volumes of high-speed deliveries are required. Drone-based delivery may contribute to ease traffic congestion in our already congested urban cities. In this paper, we established a framework for estimating the drone-based package delivery traffic densities of five EU countries. This estimation is performed for three growth scenarios (0.9, 1.8 and 3.6 percent annual growth rates) between 2035 until 2050. From the list of five countries, a case-study is presented for Paris metropolitan area. The study predicts, for a 1.8 percent conservative growth rate, that the urban airspace of Paris would need to cope with a traffic density of 63,596 drone-based deliveries of small express packages as well as fast-food meals by 2035 within an area of 12,012 km^2. The proposed method can be applied to any given city, albeit with suitable modelling assumptions. In addition, we presented a detailed analysis between an existing and a potential food-delivery transport mode. Our approach indicated a strong economic incentive to use a fleet of drones to perform food-delivery tasks. To be able to accommodate such traffic numbers, a robust airspace management system is required in order to realise commercial drone delivery.

CRediT authorship contribution statement

Malik Doole: Conceptualization, Data curation, Methodology, Formal analysis, Writing - review & editing. **Joost Ellerbroek:** Methodology, Supervision, Writing - review & editing. **Jacco Hoekstra:** Methodology, Supervision, Writing - review & editing.

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