SIMULATION OF TRANSPORT DRONES IN HAMBURG CITY WITH CENTRAL CONFLICT RESOLUTION

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Abstract
This paper introduces a simulation for the safe operation of cargo drones in urban areas. A modular workflow is adapted to simulate the transport between fixed points using the Aurelia X6 pro drone with a payload of up to 5kg. This work considers a future scenario beyond current drone regulations. A high demand is assumed, generating revenues equivalent to bicycle courier rates. The maximum distance of 15km is characterized by non-permanent visibility, indicating that operations require external safety measures Beyond Visual Line of Sight (BVLOS). Flights have to avoid no-fly zones, which are provided by Deutsche Flugsicherung (DFS) in the DIPUL system. For safe operations, flights must be separated in the air, for which separation minima are developed for the network, extending LBA recommendations. Lateral separation minima include Flight Geography, Contingency Volume, and a network buffer for interpolation gaps. Flights follow a network of predefined waypoints and segments, with parallel tracks separated by the separation minima, flying at 120m above mean sea level (MSL), providing a vertical buffer to a minimum altitude of 100m and an upper limit of 300m. Trajectories are calculated based on Aurelia's performance, resulting in 4D points to be separated. Conflicts between planned trajectories are detected at intervals and resolved by a centralized deconfliction module. The network performance of a full day's traffic is evaluated based on trip duration, detours, and resolved flights. The potential revenue from all flights is compared to landing and navigation costs, indicating the expected resource flows.

1. INTRODUCTION

Drone technology promises economic benefits, particularly in urban environments, through a variety of potential use cases [22]. Real world operations require careful consideration of operational safety, capacity, potential revenues, and cost [14,23]. A wide area of applications could result in a large number of concurrently airborne unmanned air vehicles (UAVs) that require coordinated traffic management [24]. Regulations for the operation of UAVs [3,7] provide a baseline for further concepts of operations [8,25]. Together, the use-cases and the operational constraints determine traffic patterns, such as the number of airborne drones as well as their operational parameters like range, speed and position. To investigate the interaction of demand, capacity and economic issues, modular simulation frameworks [1,9] are used.

One possible use case is the rapid and ad-hoc transport of packages by transport drones. Even in the transport use case, there is a wide range of missions depending e.g. on payload mass and size, range and operational concept. Hospitals, laboratories, office buildings or even manufacturing plants require frequent transport of packages between each other [20,21]. At these centers of demand, landing positions that provide a foundation for ground operations such as loading/unloading or charging, as well as airside integration [19] could be created. Existing drone models such as the Aurelia X6 pro can transport packages over significant distances up to 15 km [2]. However, bicycle couriers already offer point-to-point transportation of small goods in urban areas on so called “last miles” [4], which limits prices that can be charged.

For the en-route phase of unmanned flights through cities, regulatory frameworks suggest a lower limit of 100m flight altitude [7] and an upper limit of 300m [8]. No-fly zones or "geo-zones" shall be avoided [16]. However, it's not yet specified how the vehicles could fly Beyond Visual Line of Sight (BVLOS), e.g. on direct connections [10], corridors [11] or tracks [9]. The flight path concept is linked with the problem of minimum separation [26] and the resolution of possible conflicts [12] between airborne vehicles. The German Federal Aviation Office (LBA) recommendations for lateral clearance provide a basis for the distances required for a vehicle to stop, from which minimum separation can be calculated [6,15]. Conflicts should be resolved, either in the air, so that the vehicles separate themselves tactically [13], or conflicts could be resolved prior to departure [9]. Moreover, the routing concept is linked to the performance of the flights, as it determines detours, flight times, and the number of conflicts between flights. Finally, the number of flights that can be operated without conflicts, determines potential revenues of the operators, as well as for the flight’s management, provided that each flight pays a fixed amount per departure and distance.

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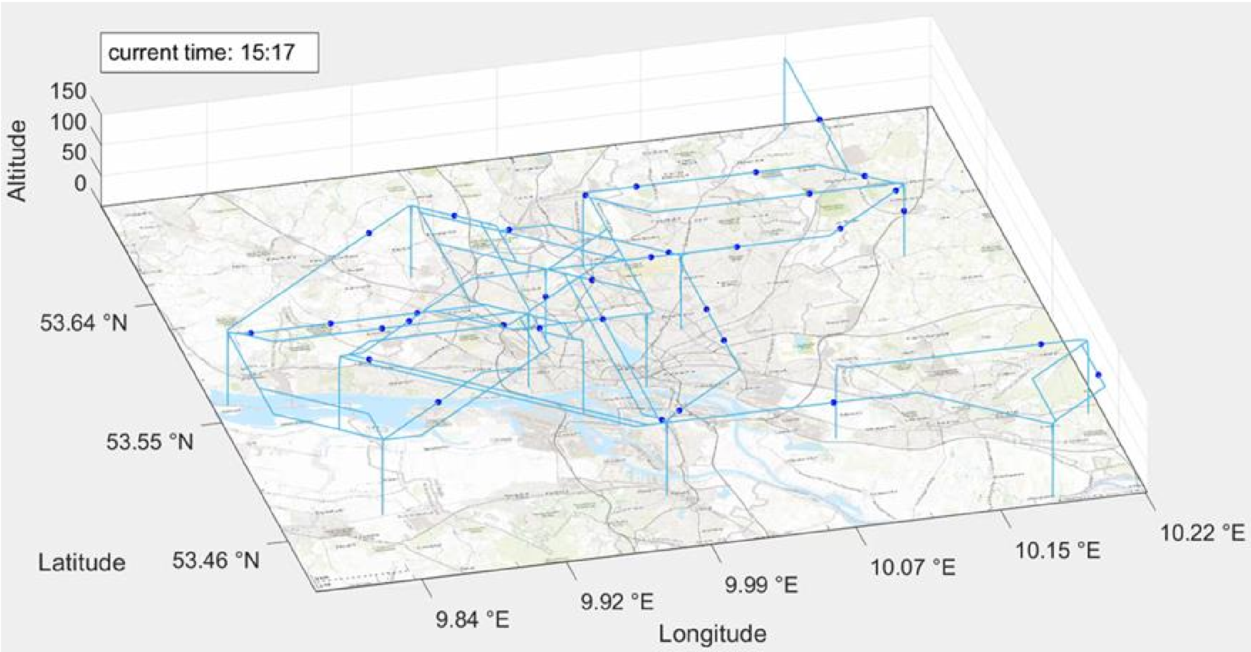

FIG. 1. Excerpt from simulation of drone transport for one day in Hamburg. Light blue lines indicate UAV routes, and dark blue dots represent UAVs.

The functionality of the drone air traffic system in Hamburg is modeled by a modular simulation in RCE [17]. Automated drone traffic is assumed. First, the use case of transporting goods between vertiports in the city of Hamburg is defined and the system boundaries are given. The system is simulated using a generic traffic demand as an input variable in a Remote Component Environment (RCE) workflow. A network of routes is generated, which avoids no-fly zones from DIPUL [5] and [17]. Trajectories are computed on these routes based on a Dijkstra algorithm [18]. The simulation investigates centralized strategic conflict detection and resolution. Traffic is visualized to provide an overview of the entire system (see Figure 1). Finally, potential revenues and costs for drone operators are calculated.

2. TRAFFIC SIMULATION

First, the use case and the scenario are defined. In the city of Hamburg, loads of up to 5 kg are to be transported between the start and destination nodes. The transport drone used is the commercial Aurelia X6 Pro, which is available at the Institute of air Transportation Systems (ILT) of the Hamburg University of Technology (TUHH). Thus, additional information not available from the manufacturer, such as the Characteristic Dimension and performance data, could be obtained (see Table 1). The input variable for the simulation is a generic demand model with a night curfew. The city is covered based on an origin-destination matrix of 17 distributed nodes.

Parameter	**Value**
Empty mass	5,4 Kg
Flight Time	55 Minutes (27 Minutes with maximum payload)
Range	15 km
Payload mass	5 Kg
Max. Flight Speed	56 km/h
Characteristic Dimension(*)	1,75 m

TAB 1. Aurelia X6 Pro Drone [2]. (*) own measurement, according to specifications by [6].

2.1. System Boundaries

The operation of drones in urban areas is subject to many conditions. In the simulation, boundary conditions and limits are derived from available documents and assumptions are made where necessary. The operating area is limited to the city limits of the city of Hamburg. The operating time is assumed to be 06-22 o'clock due to a night flight ban. The flight altitude is 120m, so that a buffer to the recommended minimum flight altitude of 100m [7] as well as to the maximum flight altitude of 300m [8] is maintained. Flights may only take off or land at the 17 defined hubs. Flights will only operate outside of designated geo-zones ("no-fly zones"). These consist of hospitals and a power plant from the DIPUL system [5] (see Figure 2) and are partially entered manually [1].

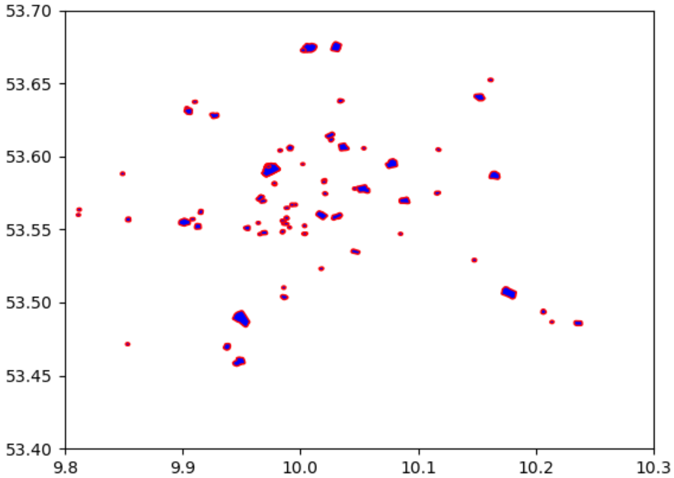

FIG. 2. No-fly zones from [5] used in the simulation in the map area of Hamburg.

Only a subset of DIPUL's geo-information areas were used in the project as combining all areas would severely limit flight operations, as shown in Figure 3.

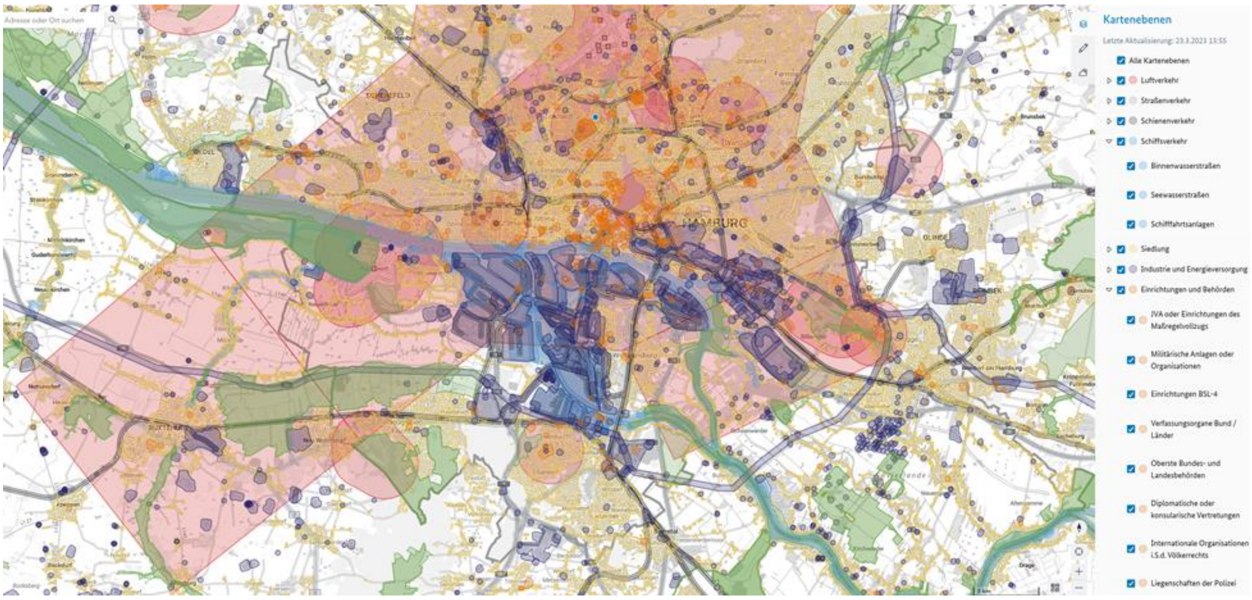

FIG. 3. Overlap of all geo-information areas in Hamburg in DIPUL [5].

Allowing for a large number of flights, a future concept is created, where flights are restricted to a route system that bypasses no-fly zones and in which parallel routes are separated with minimal separation (see Section 4.2). Vehicles must maintain minimum separations in the lateral and vertical planes at all times. In addition, there are no airspace reservations for missions.

To enable safe operations, flights are separated centrally and strategically - i.e., prior to departure time. In conflict resolution, the assumption is made that all requested flights are known at the start of the day. A mathematical optimization imposes the condition that no separation conflicts shall exist between planned trajectories and maximizes the number of conflict-free flights.

2.2. RCE-Workflow

For the simulation, modules that cover individual urban air transportation areas are linked in an RCE workflow (refer to Figure 2). In RCE, an entire day is simulated in a sequential chain of functional modules. The output of the previous module is used as the input for the next module. The information is transferred from module to module through the Common Parametric Aircraft Configuration Schema (CPACS) XML-based data format. The package drones use case extends the workflow initially used for UAM [1].

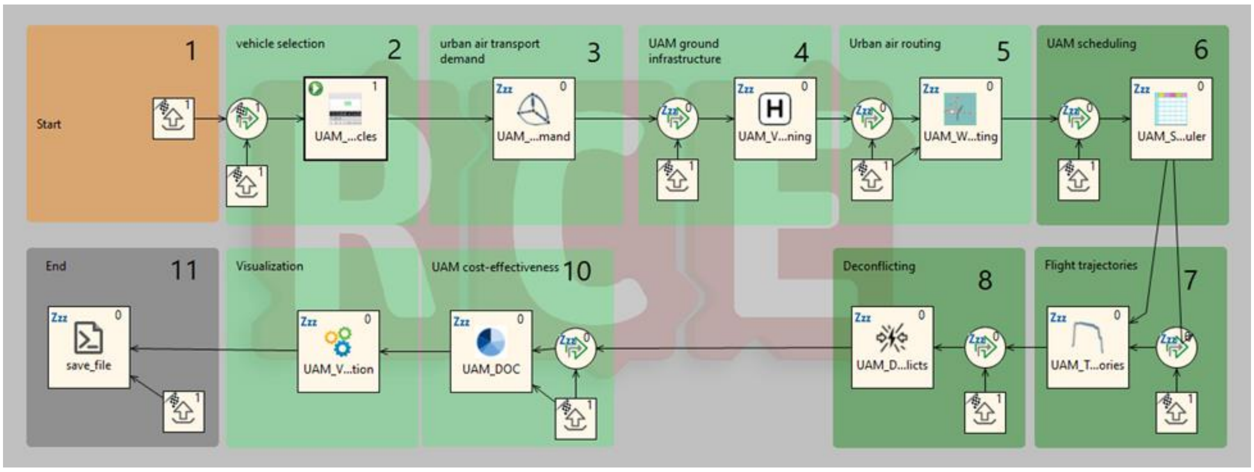

FIG. 4. RCE workflow of functional chain for transport drone simulation.

2.3. Minimum separation and Contingency Volumes

A challenge for UAS operations is the safe separation of large numbers of vehicles in the air. One requirement for operational authorization is to reserve an exclusive operational volume for each individual flight, including safe separation distances (see Figure 5) [27,6]. If a volume is reserved around the entire flight path, operating UAVs with a range of 15 km and a flight time of about half an hour reserve a large part of the urban airspace for a relatively small number of flights To allow a larger number of simultaneous flights (like in Figure 1) in the urban area, a more fine-grained separation concept is required. However, no formal applicable separation limits have been officially yet defined. Therefore, a minimum separation was derived from the LBA recommendation. Conceptually, instead of reserving the entire operational area for the entire duration of the flight, only the area around the vehicle at any given time is reserved, comparable to [26]. If two such areas around each vehicle do not overlap, they can be used for vehicle-to-vehicle separation. This idea is then extended to short flight intervals where separation must be maintained. In this way, an approximation of a possible separation value is made for simulation purposes.

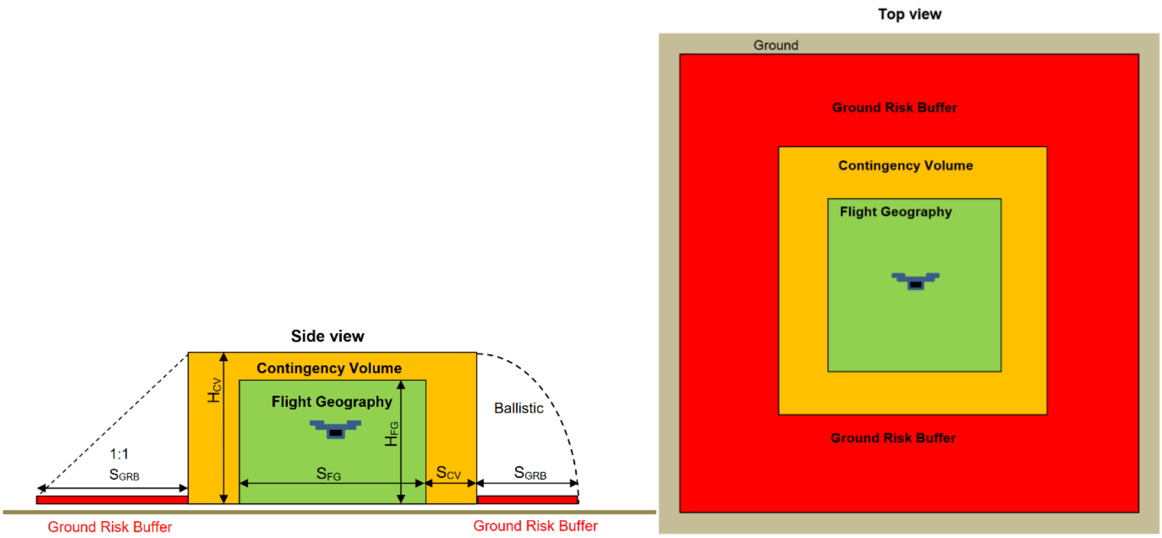

FIG. 5. Operational Volume contains the Contingency Volume and the Flight Geography, figures taken from [6].

The following contingency volume has been calculated for the Aurelia X6 Pro using the formula from the LBA recommendation [6] (see Table 2). The reaction time t of one second is an assumption that covers all information processes in an automated system. The Flight Geography S_{FG} consists of the minimum value of three times the characteristic dimension [6] (see Table 1). The contingency volume consists of GPS inaccuracy, position holding error, map error and a reaction distance [6].

Parameter	Symbol	Value
Horizontal Speed	v	12,5 m/s
Reaction Time	t	1 s
Flight Geography	S_{FG}	5,355 m
Contingency Volume	S_{CV}	27,5 m

TAB 2. Parameters for determining the Contingency Volume of the Aurelia X6 Pro drone, based on [6]

Vehicle-to-Vehicle Separation

A minimum separation of two vehicles can be calculated from the extent of two operational volumes, that are composed of a flight geography and contingency volume (see Figure 6).

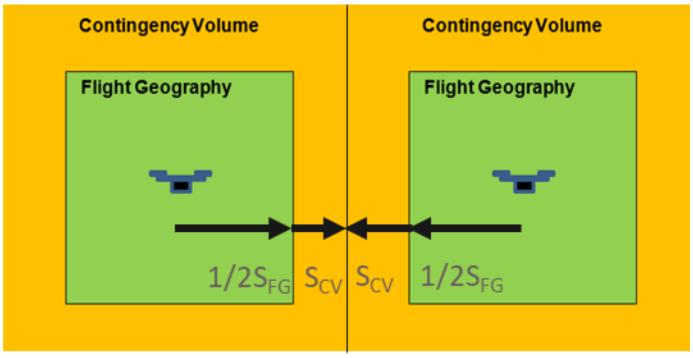

FIG. 6. Minimum vehicle separation derived from two operational volumes that contain contingency volume and flight geography, figure extends [6] (not true to scale).

The operational volume represents the maximum distance a vehicle traveling at full speed would need to come to a complete stop, containing position error and reaction time [6]. It follows that if the operational volumes of two vehicles do not overlap, in a situation where two vehicles are approaching each other, a stop signal would cause both vehicles to stop within their volumes, i.e., before they meet. Equation (1) gives the minimum required separation distance of S_{VV0}= 60,355 meters:

$$S_{VV0} = 2(1/2S_{FG} + S_{CV}) \quad (1)$$

$$= S_{FG} + 2S_{CV}$$

$$= 5{,}355\text{m} + 2\cdot 27{,}5\text{m}$$

$$= 60{,}355\text{ m}$$

This minimum separation is a value for the separation of two vehicles at a given time. **This separation value does not guarantee a safe flight operation and therefore must not be used in real operations.** The original calculation of operational volumes in [6] is intended for the calculation of safety distances in more coarse-grained situations. Before applying such new separation distances, it must be ensured that the underlying assumptions are also valid for the case of instantaneous vehicle separation.

Separation of vehicles in the network

The challenge of separation in the pre-departure network is that the interpolated trajectories must be separated from each other. After interpolation, the central conflict detection detects whether a conflict exists in time steps of 10s. Thus, there is a gap in the intermediate time in which no detection takes place. The separation should also be maintained in the interim period (see Figure 7).

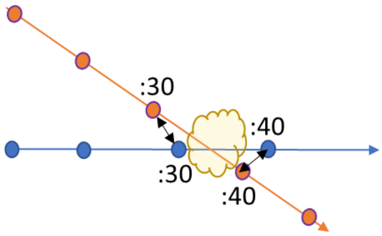

FIG. 7. Vehicle separation challenge between interpolated trajectories.

Therefore, an additional buffer must be added to ensure that trajectories that are only checked every 10 seconds always maintain the minimum distance. From the worst-case scenario, where both vehicles head straight for each other, the distance that both vehicles travel in that time must be added (see Figure 8). In total, a network limit of 310,355 can be calculated in Equation 4. This additional buffer can also accommodate minor deviations of flights from their planned trajectories during operations.

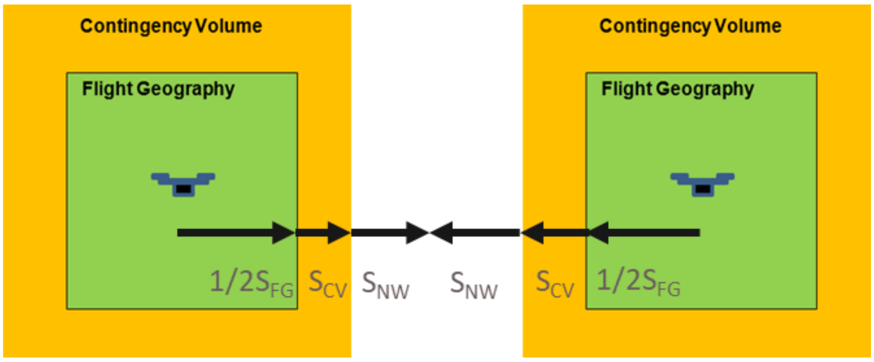

FIG. 8. Concept for minimal vehicle separation between interpolated trajectories

$$t_{NW} = 10s \quad (2)$$

$$S_{NW} = v \cdot t_{NW} = 10s \cdot 12{,}5m/s = 125m \quad (3)$$

$$S_{VV} = 2(1/2S_{FG} + S_{CV} + S_{NW}) \quad (4)$$

$$= S_{FG} + 2S_{CV} + 2S_{NW}$$

$$= 5{,}355m + 2 \cdot 27.5m + 2 \cdot 125m$$

$$= \underline{310{,}355m}$$

In the workflow, the deconfliction module reads the trajectories of all potential flights and detects separation conflicts before departure. The number of flights is then maximized under the constraint that there are no conflicts [9].

2.4. Revenue and cost model for drone transportation

Drone transport of small loads is in competition with bicycle couriers, which offer comparable transport services for loads up to 8 kg from Monday to Friday from 07:00-19:00 [4] as transport drones in the concept presented here.

In the simulation, the revenues for drone transport are equated to the prices charged by the bicycle courier KURIER AG for the transport of parcels (see Table 3).

Parameter	**Value**
Basic charge	8,34€ (12,38 € to 2km)
Cost per km	2,02€/km

TAB 3. Revenue for drone operators in simulation, analogous to [4]

The cost to drone operators associated with take-off and navigation are assumed to be as follows (see Table 4):

Parameter	Value
Take-Off Charge	1€
Navigation Charge	0.2€/km

TAB 4. Assumption of costs for drone operators in the simulation

3. RESULTS

In the simulation, an all-day scenario is calculated for the city of Hamburg. Only cargo drone transports are considered.

3.1. Routing

A critical aspect of the simulation is the routing, which includes a predefined grid of nodes. Each node is connected to its eight neighboring nodes by segments [9]. Segments or nodes that intersect a no-fly zone are excluded from the network. The shortest routes between each origin and destination are then determined, minimizing directional changes (see Figure 9). The minimum separation distance S_{VV} (see Equation 4) between parallel lines ensures that there are no conflicts between parallel flights.

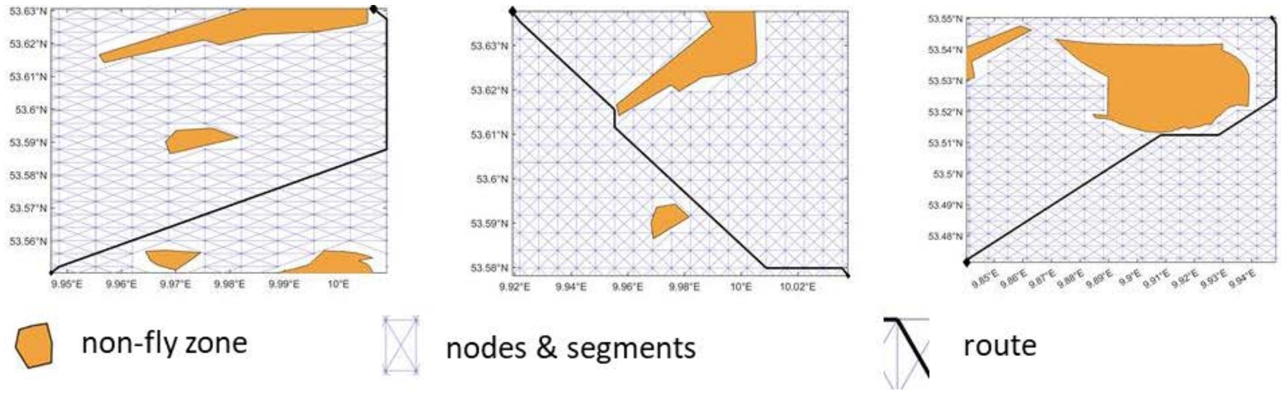

FIG. 9. Three example routes

Detours are required for routes due to no-fly zones and the route segments. The distances covered by the routes differ from the great circle distances (see Figure 10). Of the 101 demand pairs, 65 are within the Aurelia X6 Pro's maximum range of 15 km for great circle distances (see Table 5). However, two origin-destination pairs cannot be accommodated due to detours. All routes in the simulation fall within the operational great circle range.

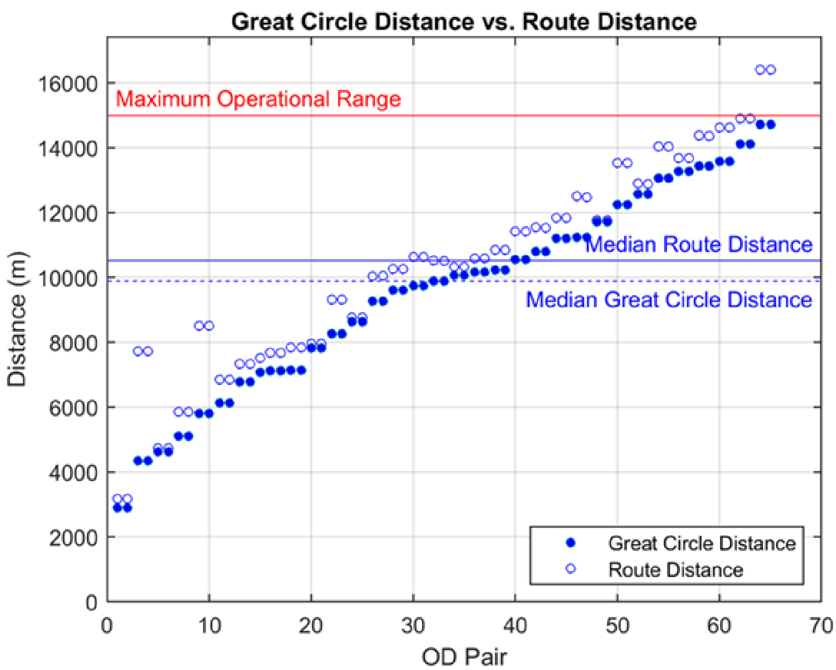

FIG. 10. Origin-Destination pairs and maximum range (origin-destination pairs above the maximum range cannot be operated)

Parameter	Number
Demand Pairs (Origin-Destination)	101
In Great-Circle Distance	65
In Route-Distance	63
In Great-Circle Distance but Beyond Operational Range	2

TAB 5. Number of routes of the scenario in Hamburg

The evaluation of the routes shows that the total route distance is 639.6km (see Table 6). The mean route distance is 10.2km and the mean deviation of the route distance from the great circle distance is 10.3%.

Parameter	Value
Total Great-Circle Distance	590,2 km
Total Route Distance	639,6 km
Mean Great-Circle Distance	9,4 km
Mean Route Distance	10,2 km
Mean Detour	10,3 %

TAB 6. Route-parameters for all origin-destination pairs

3.2. Central Pre-departure conflict detection and resolution

The planned trajectories are passed to the central conflict detection and resolution system. Of the 3,088 planned flights, 2,810 flights have at least one separation conflict in 6,106 conflicting flight pairs. A conflicting flight pair may have multiple point pairs in conflict. Their number is 25,411. Conflict detection requires 75s and conflict resolution requires 12s. Conflict resolution allows 1,546 flights without conflicts, about half of the demand.

3.3. Revenue and Costs

With the assumptions made, the following are calculated the revenues and costs for one day of drone transport operation as follows (see Table 7):

Parameter	Value
Total revenue	45.324 €
Landing fee	1.546 €
Navigation charge	3.211 €
Total fee (Landing + Navigation)	4.757 €
Share of fees in total revenue	10,5 %

TAB 7. Revenue and costs for drone operators for a simulation day

4. CONCLUSION & OUTLOOK

In this paper, a full-day simulation of parcel transport between demand locations was investigated for the city of Hamburg. A modular workflow includes an approach for minimum distance calculation based on position uncertainties, stopping distances and network effects. The routing system is evaluated for detours and origin destination pairs in the operational area. From these, a set of flights is computed that maximizes traffic under the constraint of no conflicts between planned routes. Using bicycle courier fees as an estimate of the potential revenue for transport drones, the revenue for these operations is calculated. A portion of this is considered to be the revenue for air traffic management.

A total of 1,546 conflict-free flights were computed on 63 routes between 17 nodes, with an average detour of 10.3%. For this purpose, system parameters such as flight altitude, route network, separation minima, etc. for drone transport were integrated into the simulation. An economic analysis of the whole system was performed, which showed a total revenue of €45,324 for a single day of operation for the transport providers, of which a fee of €4,757 (or about 10%) is paid for traffic management. This first conceptual simulation setup is only a first rough estimate of operations and costs. Dynamic interventions by e.g. police or rescue services as well as a more realistic cost analysis are required for a more reliable value analysis and feasibility assessment. While this actual analysis of flight planning and deconfliction is based only on the strategic level (beginning of the operational day), the next step will also address a step-by-step update of planning and deconfliction during the tactical operational phase.

Setting the revenue for drone transport at the same level as the revenue for bicycle couriers provided an initial estimate of potential revenue based on actual operations. Assuming air traffic management fees of about ten percent of revenue, nearly two million euros will be accumulated per year. If urban ATM is to require more funding, more value would have to be generated by the flights or a larger proportion would have to be charged. Improvements in speed, flexibility or reliability could justify higher prices, for example for transporting medical supplies. Additional use cases such as aerial surveillance or air mobility could provide additional value to the city, as well as more funding for communications, navigation, surveillance and management infrastructure.

Future work should explore the interplay of urban air transportation with more diverse use cases. The relationship between different routing concepts and conflict resolution should be further investigated. Since flights may deviate from planned trajectories, the maximum number of flights that can be safely operated would be lower than a set of flights that is deconflicted before departure. Integrating more takeoff and landing sites, areas for continuous surveillance operations, or even the ability to deliver goods to end users could lead to higher demand for more traffic in the skies.

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CONFLICTS OF INTERESTS

The authors declare that they have no conflicts of interests that are directly or indirectly related to this publication.

ABBREVIATIONS

ATM	Air Traffic Management
BVLOS	Beyond Visual Line of Sight
CPACS	Common Parametric Aircraft Configuration Schema
DIPUL	Digitale Plattform Unbemannte Luftfahrt
DLR	Deutsches Zentrum für Luft- und Raumfahrt
LBA	Luftfahrt Bundesamt
MSL	Mean Sea Level
RCE	Remote Component Environment
S-CISP	Single Common Information Service Provider
UAV	Unmanned Aerial Vehicle
USSP	U-Space Service Provider
XML	Extensible Markup Language
SCIP	Solving Constraint Integer Programs

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