An Agent-based 3D Urban Air Network for the Freight Distribution Problem

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Abstract

Advances in new electric aerial vehicles have encouraged research on pioneering Urban Air Mobility (UAM) scenarios, proposed as eco-sustainable solutions capable of delivering services for passengers, goods, and emergency operations —while simultaneously reducing traffic congestion, travel times, and environmental impacts. These aerial-based services require the support of a suitable Urban Air Network (UAN), which must comply with a set of constraints defined by the specific characteristics of this emerging form of mobility. In this framework, one promising application domain is last mile freight transportation, which is the focus of this paper. Aerial freight transport will benefit from the use of flying vehicles moving also along the third (vertical) dimension to fulfill the basic requirement of connecting origin and destination points while ensuring both safe aerial routes and adequate vehicle separations. To achieve this, the 3D UAN is considered, modeled as a multi-layered structure composed of several 2D graphs –one for each layer– allowing for vehicle routing within the lower airspace. Each link in the network is associated with a cost function, enabling the computation of shortest paths between origin/destination pairs. Moreover, the links are dynamic and can be activated or deactivated to reflect varying capacity constraints. To ensure both safe aerial routes and adequate vehicle separations between flying vehicles moving along the links of the network, in addition to the 3D-UAN model an agent-based framework has been set, which is based on a distributed architecture. The preliminary results from a simulated test case offer promising insights, which will contribute to shape the design of future urban aerial logistics systems.

Keywords

Freight distribution, Vertical links, Dynamic links, Multiagent systems

1. Introduction

In the coming years, emerging Urban Air Mobility (UAM) scenarios [1] are expected to be realized, leveraging Unmanned Aerial Vehicles (UAVs) —whether remotely piloted or fully autonomous— to enable a wide range of aerial services at low altitudes, and taking advantage from the vertical dimension for avoiding ground traffic congestion in urban and metropolitan areas [2]. For instance, these applications may include on-demand and scheduled services, like air taxis, cargo transport, airport shuttle, as well as emergency response, news coverage, and real-time traffic, agriculture and weather monitoring [3, 4, 5, 6, 7, 8]. All of them are envisioned to be predominantly operated by electric Vertical Take-off and Landing (eVTOL) vehicles, which offer a substantially lower environmental impact compared to traditional helicopters. These vehicles will utilize *vertiports* as essential hubs for access and egress within the UAM system [9, 10].

To enable such flight services, which primarily operate within the uncontrolled ICAO Class G airspace [11], some Urban Air Network (UAN) models have been developed. Their structure and characteristics will be shaped by the specific nature of the aerial services they support and the degree of integration required with existing ground transportation networks. Moreover, most of them are modeled by combining graph representations —consisting of nodes and links— with performance metrics, particularly cost functions assigned to each link [12], and in the respect of safety protocols, environmental impact mitigation, and operating constraints [13, 14, 15].

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UAN structures are expected to provide key advantages, including: (*i*) seamless connectivity between Points of Interest (POI), (*ii*) reduced travel times and optimized travel distances, and (*iii*) safe and efficient flight corridors. To fully realize these benefits, UANs must integrate a communication network where Flying Vehicles (FVs) and ground infrastructure continuously exchange real-time data. This exchange is critical for enabling an advanced air traffic system that ensures safety, prevents sky congestion, and optimizes FV operations. Efficient coordination will also be essential for managing takeoff and landing sites, maintaining safe airspace separation, and adapting to dynamic urban conditions. Achieving this level of integration will require leveraging cutting-edge technologies such as AI-powered traffic control, communication, and predictive analytic to proactively address potential challenges [16, 17, 18].

These elements mirror the concept of Cooperative, Connected, and Automated Mobility (CCAM) [19]. In fact, by utilizing advanced communication technologies such as Vehicle-to-Vehicle (V2V) [20] and Vehicle-to-Infrastructure (V2I)) [21] systems (e.g., Flying Ad-hoc NETwork (FANET) [22] and Wireless Sensor Networks (WSNs) [23, 24]), CCAM enables seamless interaction and efficient coordination among Connected and Automated Vehicles (CAVs), by enhancing safety and optimizing traffic flows.

To control and manage low–altitude urban air traffic, centralized or distributed approaches can be adopted [25, 26]. Each of them has advantages and disadvantages. Centralized systems [27, 28] are simpler to be implemented and allow to control FVs, routes and infrastructure information on the whole urban air space in a single point that, however, represents also the critical point in case of failure [29]. On the other hand, distributed approaches for air control are more complex both to be implemented and for maintaining the safety of routes [30]. Moreover, when routes among POI (like vertiports) are fixed, an intermediate distributed solution could consist in pairing autonomous flying vehicles and local air traffic control. However, the presence of natural or anthropogenic obstacles —such as tall buildings or urban canyons— may hinder the effective operation of both centralized and distributed systems for low-altitude urban air traffic control [31]. Therefore, under these conditions, safe route management must be autonomously handled by FVs through the use of on-board technologies [32]. This solution has been also widely evaluated across various scenarios to address the expected increased density of low-altitude aerial services [33].

Regardless of the adopted solution, setting a UAN would define clear rules for UAV air navigation. Recently, in [34] a three–dimensional Urban Air Network (3D-UAN) model including the third (vertical) dimension has been proposed and calibrated. It allows to link trip origin/destination points as a sequence of aerial, dynamic links where a suitable cost function has been defined. Building on this 3D-UAN model, the paper explores its application to the last mile freight distribution between suitable POI, by delegating trip safety to individual FVs. For this purpose, FVs are assumed to be fully autonomous, equipped with appropriate on-board systems, and constrained to operate within predefined air corridors, altitudes, and speeds according to a designated pre-flight plan approved by the Air Traffic Control (ATC).

The goal of this study is to test the 3D-UAN model in [34] by considering a distributed agent-based framework in order to check its performances with respect to an equivalent ground-based freight distribution system. It is worthwhile to note that FVs and corresponding communication structures, as well as rules and operational issues, are still under development, so that the results of this study have to be considered an exploratory analysis contributing to setting suitable operational architectures in the context of UAM models. Particularly, the paper intends to provide a reference framework, to be further developed, for starting analyzing advantages, disadvantages and limits that would arise in the operational implementation of a real-world last mile air delivery problem.

To analyze the considered scenario, we carried out an experimental test on a reference 3D-UAN by adopting an agent-based simulator in which FVs are implemented as autonomous software agents pursuing their respective objectives. Intelligent software agents (hereafter referred to simply as agents) have been widely adopted in modeling and managing various aspects of both ground and aerial transportation systems, across multiple levels of abstraction [35, 36, 37, 38] thanks to their adaptive, learning, proactive, and social capabilities [39], as well as their ability to operate in large-scale centralized or distributed environments, even under uncertainty or dynamic conditions [40, 41]. Regarding the aerial network model, it is worthwhile to note that legal and regulatory aspects are still in progress and cannot be considered fully established. However, in this work reference has been made to the current EU/US low airspace intended organization and the considered 3D-UAN is meeting such general requirements.

The remainder of the paper is organized as follows: Section 2 provides an overview of the related literature on UAN models that incorporate the vertical dimension, including agent-based approaches. Section 3 briefly outlines the 3D-UAN model introduced in [34]. The agent-based framework is presented in Section 4, while Section 5 describes the simulations and Section 6 reports the results by discussing findings and direction for future researches.

2. Related Work

Autonomous UAV flight has attracted increasing attention of scientists, particularly in relation to the operational and regulatory challenges of enabling fully unmanned aerial missions based on a free-flight airspace approach [42]. This increased interest has lead to important advancements in UAV technologies [43], including propulsion, software, sensors, and communication systems, which have paved the way for a new generation of safe, efficient, and eco-friendly electric aerial vehicles [44, 45]. Leveraging on a third spatial dimension, these vehicles hold the potential to alleviate urban congestion, reduce travel times, and minimize environmental impacts, particularly in large metropolitan areas [2]. In this context, ground and low-altitude airspace constraints are mainly mapped by using 3D Geographic Information System (GIS) technology, while strategic UAM routes are determined through collision-avoidance algorithms [46, 47, 48]. To establish a fully operational urban aerial mobility ecosystem, a comprehensive technical and organizational framework is essential [1, 49]. Such a framework must ensure safe operations, efficient airspace management, and seamless integration with conventional aviation to prevent hazardous interactions [50, 51]. However, a large part of the existing literature primarily examines the characteristics and potential constraints of lower airspace, while failing to address the task of modeling UANs.

Among the most interesting proposals, in [30] the uncontrolled urban airspace (Class G) is modeled as a multilayer network system, where each layer consists of aerial corridors representing links between nodes, and vertical transitions between layers occur at designated nodes. Flight paths are regulated by speed limits, designated headings, maximum traffic capacities, and V2V communications [20], allowing FVs to navigate corridors and nodes autonomously, without direct reliance on a centralized control system. The geometric configuration of these aerial corridors is determined by three key factors: (*i*) the type of flying vehicle, (*ii*) the spatial distribution of Points of Interest (nodes), and (*iii*) the presence of fixed obstacles within the Urban Air Network.

Finally, to ensure safe operations and optimize urban aerial services, the Metropolis project [52] introduces four distinct layered urban airspace concepts: (*i*) Full Mix – A non-structured free-flight scenario where aerial vehicles navigate based on on-board equipment, adhering to physical constraints such as weather and fixed obstacles. This model considers aerial corridors and nodes at corridor intersections or vertiport locations. (*ii*) Layered Structure – Airspace is divided into horizontal layers, each with a defined structure. Transitions between layers occur at specific nodes, and vehicle separation is determined by position, speed, and altitude regulations. (*iii*) Zonal Structure – Circular zones function similarly to ground roundabouts, by directing air traffic, while radial zones facilitate movement between them. (*iv*) Tube Network – A structured system with predefined, conflict-free routes forming a 3D network. Nodes represent key waypoints, while tubes serve as links between them. Vehicle separation is based on altitude and time, with short-range flights occupying lower levels, while long-range flights are assigned to higher altitudes.

In contrast, AirMatrix [53] organizes lower urban airspace into a structured UAN composed of standardized air blocks distributed across multiple layers. Each layer contains a varying number of air blocks, where FVs navigate according to predefined constraints such as waypoint limits, crossing points, and flight flexibility. FV trajectories are designed as foundational structures for UAM services, with vehicles departing from designated waypoints and traveling through sequential corridors via intermediate waypoints until reaching their destination. Simulations indicate that further refinements are necessary to efficiently accommodate the growing volume of FV operations.

Another UAN model is the Dynamic Delegated Corridors (DDCs) [54], which structures airspace into dynamic volumes or tunnels similar to traditional airways. In this model, separation management is delegated to FVs, supposed equipped with see-and-avoid capabilities, high-precision navigation systems, and V2V communication. Corridor dimensions and operational status (i.e., open or close) are dynamically adjusted based on weather conditions and air traffic density as needed. Additionally, DDCs incorporate an Automated Decision Support system, functioning as a dynamic UAN model that enables or disables individual corridors based on predefined criteria, by optimizing airspace utilization and enhancing operational efficiency.

Recently, an air traffic planning methodology has been presented in [55]. It uses fixed-routes modeled as a graph –i.e., volume segments act as two-way links, while vertiports (named droneports) and delivery points act as nodes. Vertical links connect the horizontal volume segments, while node complexity is represented by means of a cylindrical airspace volume. In addition, some other quantities are defined, i.e., (*i*) an objective function incorporating temporal and spatial information, such as link congestion and operational efficiency, to measure vehicle interaction and (*ii*) a two-step algorithm to both balance the path complexity in Origin/Destination (O/D) pairs and manage congestion.

Additionally, some research integrates digital twin models with UAN frameworks [56] to enhance situational awareness. This approach leverages dynamic data to identify critical elements such as ground access points, obstacle heights, and optimal flight paths, by enabling more efficient and adaptive UAM solutions.

With respect to freight delivery, hub-to-hub connections are often assimilated into broader UAV flight paradigms and typically modeled by using established frameworks from the literature on autonomous aerial navigation –incorporating constraints such as route planning, obstacle avoidance, and flight stabilization– and frequently assuming a high level of on-board intelligence and autonomy [57, 58]. Finally, a significant body of work focuses on "last-mile" delivery scenarios, where UAVs operate in highly dynamic and constrained urban environments [59, 60]. In these cases, navigation and control are almost exclusively delegated to on-board systems, without reliance on external guidance or centralized air traffic control. This trend underscores the growing emphasis on distributed autonomy and real-time adaptability, which are essential prerequisites for scalable and resilient UAM infrastructures. Consequently, the same assumptions are often extended to freight transport networks, especially for short-range or intra-urban hub connections [6].

Software agents are extensively adopted in conventional transportation systems [61, 37] and are increasingly being applied in UAM scenarios because the distribution of intelligence across the several actors in the system facilities the modeling, management, and simulation of low-altitude aerial mobility. Particularly, the versatility of agent-based frameworks to represent different UAN models has been presented in [62]. Based on the open-source multi-agent transport simulation framework MatSim [63], a dedicated UAV module incorporates UAM scenarios into ground-based transportation systems, to perform comprehensive analyses that includes also the combined air-ground transportation system. The approach proposed by Ho et al. in [64] integrates scheduling elements into Multi-Agent Path Finding (MAPF) solvers, by enabling dynamic adjustments to UAV takeoff times and speeds to resolve conflicts. Two conflict resolution techniques are introduced: takeoff scheduling, which delays UAV departure, and speed adjustment, which reduces a UAV speed along specific flight path segments. The effectiveness of MAPF has been tested in a high-density UAV scenario over Tokyo. The study in [65] focuses on the safe integration of UAVs into the Air Traffic System by developing a simulation framework for risk and impact assessment. By using Agent-Based Modeling and MonteCarlo simulations, air traffic data is analyzed to replicate realistic scenarios. The research analyses three distinct environments: a terminal area (e.g., a vertiport), a rural region, and an entire state with varying traffic densities and operational conditions. Another notable simulator supporting multi-agent UAV applications [66] incorporates realistic UAV physics and dynamics while offering a 3D visualization. However, it does not model a UAN. That said, a vast array of UAM simulators leverage agent-based technology. For a more comprehensive overview, readers may refer to existing surveys and comparative analyses in the literature, such as [67, 68, 69].

In the contest above described, the research gap that this paper intends to fill refers to the use of the 3D-UAN network for the freight distribution problem by using an agent-based framework with a distributed architecture, which has not been considered yet. Therefore, based on the 3D-UAN model [70] –which will be synthetically described in the next section– this study will address the freight distribution problem realized by FVs in the context of a UAM scenario. A distributed agent-based architecture is used to model FVs and suitably located communication points within the 3D-UAN.

3. The Network Model

The 3D-UAN model proposed in [34] and [70], originally designed to support aerial services in very low and uncontrolled airspace [71], is here applied to a freight distribution scenario. In this context, each FV that has to travel from an origin O to a destination D must communicate a detailed flight plan to the traffic control authority, which will authorize it after checking its consistency with other flight plans. In the following, O and D will be identified also as "hubs", and may correspond to vertiports or platforms dedicated to freight loading/unloading. The flight plan must specify the required air corridors, flight altitudes, and speeds. During its flight, each FV is assumed to be autonomous, relying entirely on on-board systems, and to communicate in real-time with nearby vehicles and infrastructure, sharing data such as position, speed, operational status, and environmental conditions via Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure/Vehicle-to-Everything (V2I/V2X) protocols [72, 20, 21].

In the following, a short overview of the 3D-UAN model proposed in [70] is provided, and then the features of the freight distribution framework using a 3D-UAN model is described.

3.1. The 3D UAN model

The vertical dimension of the 3D network is organized in layers, which are separated by a fixed distance. For each layer $L \in UAN$, a 2D graph G_L is defined, formed by the sets of (*i*) fixed nodes $\langle N_{F,L} \rangle$ (i.e., access to and egress points from the UAN, as vertiports –or hubs–, or specific freight platforms and similar), (*ii*) transition nodes $\langle N_{T,L} \rangle$ (i.e., nodes where horizontal crossings and vertical shifts to an upper or lower layer are enabled) and (*iii*) dynamic links $\langle D_L \rangle$, which are corridors connecting two fixed/transitions nodes on the same layer or two fixed/transition nodes between two layers (i.e., $D_L = d_{m,L} \mid m = 1, 2, \cdots, K_L$, where $d_{m,L}$ is the generic dynamic link at layer L and K_L is the total number of links for that layer) –note that the terms link and arc will be used indifferently. In details, dynamic links are enabled or not on the basis of traffic capacity and environmental conditions. In addition, their geometrical features may change depending on the FV characteristics and safe distance, while FV energy consumption among two fixed nodes (e.g., vertiports) provided with recharging facilities imposes the link length [73]. Furthermore, FV size impacts on the vertical layers separation to guarantee suitable protection volumes around FVs [74].

In detail, for a given layer L, D_L consists of horizontal $D_{h,L}$ and vertical link $D_{v,L}$ subsets, $D_L = \langle D_{h,L}, D_{v,L} \rangle$, where:

$$D_{h,L} = \{h_{m,L}\} \in D_L \mid m = \{1, 2, \cdots\} \quad \text{and} \quad D_{v,L} = \{v_{m,L}\} \in D_L \mid m = \{1, 2, \cdots\}$$

FV landing, take-off maneuvers and layer transitions are permitted only on links belonging to $D_{v,L}$, while for a given origin/destination pair FVs move on links belonging to $D_{h,L}$, which in turn belong to the corresponding horizontal 2D graphs (G_L), and may change layer only at transition nodes. Therefore, the resulting 3D Graph (Θ) includes the horizontal graph G_Ls for each layer L (i.e., one or more depending on the UAN structure) and the subset $D_{v,L}$, i.e. $\Theta = \bigcup_{L=\{1,\cdots,n\}} G_L \cup D_{v,L}$, with $G_L = (N_{F,L}, N_{T,L}, D_{h,L})$. In the following the subscripts L and m will be omitted and explicit reference to the generic layer L or the link m will be made when needed.

Each link of Θ is associated with a cost function $c(T_t, T_g)$ defined as:

$$c(T_t, T_g) = \begin{cases} T_{t_i} & \text{for } i = 1 \\ T_{t_i} + T_{g_{i,i-1}} & \forall\, i > 1 \end{cases} \tag{1}$$

where: (*i*) i is the i-th FV using that link at a given time; (*ii*) T_{t_i} is the travel time of i on the generic link, depending on link features; (*iii*) $T_{g_{i,i-1}}$ is the time gap between i and $i-1$.

For horizontal links, T_{t_i} corresponds to the running time T_{r_i}. Therefore, if $i = 1$ it only depends on FV features and air rules, but when more FVs are on the same link, (i.e., $i > 1$) a separation $T_{g_{i,i-1}}$ between two subsequent FVs is needed to maintain safe travel conditions. For vertical links, T_{t_i} depends on the link direction towards upper (i.e., T_{a_i}) or lower (i.e., T_{f_i}) layers, and $T_{g_{i,i-1}}$ still defines the vertical time separation between two FVs. Therefore, the cost function (1) can be specialized with respect to horizontal ($c_{h,L}(T_r, T_g)$) and vertical links ($c_{v,L}(T_a, T_f, T_g)$).

Note that for sake of simplicity, the cost functions are assumed to be deterministic by imposing both ideal times and network status, although the travel time depends on both internal and external, random factors, such as schedule delay or weather conditions. In detail, assuming deterministic cost functions would lead to times and network status corresponding to ideal conditions. In such ideal conditions external and/or internal disturbances do not exist and therefore the final status might be considered the best (or ideal) one. Therefore, simulating such ideal condition provides a benchmark for identifying the optimal system performances. From a modeling point of view, including random effects in cost functions will require assuming a probability distribution for the involved variables. In general, such distribution functions for ground networks are chosen based on the coherence between model results and collected data. However, in this case the system is not operational yet, although at a first attempt distribution functions might be chosen similarly to cost functions for traditional commercial air services.

Finally, to ensure regulated departures from fixed nodes N_{F_L} and achieve an effective flow distribution across the 3D-UAN, FVs must adhere to a designated headway time at each fixed node prior to departure. This headway time, described by the function $h(I_{N_F})$, interpreted as a waiting time component, is computed as:

$$h(I_{N_F}) = I_{N_{F_i}} + \sum_{j=1}^{n-i} I_{N_{F_{i-j}}} \tag{2}$$

where I_{N_F} is the headway time of each FV before take-off, and depends on the variables $T_{r_{i-1}}^{h_{mL}}$, $T_{a_i}^{v_{mL}}$ and $T_{g_{(i,i-1)}}^{d_{mL}}$, respectively designed for each dynamic link h_{mL} ,v_{mL}, and d_{mL}. Therefore:

$$I_{N_F}(T_{r_{i-1}}^{h_{mL}}, T_{a_i}^{v_{mL}}, T_{g_{(i,i-1)}}^{d_{mL}}) = \begin{cases} T_p + T_{g_{(i,i-1)}}^{a_{mL}} & \text{if } i-1 \text{ is ahead of destination node } N_{T,L} \\ T_p & \text{if } i-1 \text{ is beyond destination node } N_{T,L} \end{cases} \tag{3}$$

In (2) and (3), (*i*) i is the i–th FV departing from the generic fixed node N_{F_L} and moving to the generic transition node N_{T_L}L, (*ii*) j refers to the FV ahead i, n is the total number of flying FVs at a given time, and (*iii*) T_p is set to $T_p = T_{r_{i-1}}^{h_{mL}} + (T_{a_i}^{v_{mL}} + T_{g_{(i,i-1)}}^{h_{mL}})$. In other words, each FV must wait at a fixed node a headway time $h(I_{N_F})$ to avoid collisions with other FVs at the transition nodes so that FV separations will be respected. Finally, the generalized link cost function is given by combining $h(I_{N_F})$ and $c(T_t, T_g)$. Table 1 summarizes the main characteristics of the cost functions.

After defining the cost functions, then the O/D travel cost –based on the minimum cost criteria and depending on link cost features, as well as on the number of FVs on the path in the given reference time– can be computed by using iterative shortest path algorithms as [75, 76, 77, 78]. An imposed criteria consists of allowing only a limited number (depending on route length) of layer switches to save battery autonomy [79] and travel time [79]. Observe that potential priorities, based on flight type –e.g., passenger, freight, emergencies– might influence the formulation of a flight plan. In general, prioritization plays a crucial role in maintaining the desired quality of service within UANs, a task that becomes increasingly complex with a growing number of operators and FVs.

Table 1
Cost functions for the 3D-UAN model

Travel Time	(T_{t_i})
Separation Time	$(T_{g_{i,i-1}})$
Horizontal links	
$T_{t_i} = T_{r_i}$	for i=1
$T_{t_i} = T_{r_i} + T_{g_{i,i-1}}$	$\forall i > 1$
Vertical links: upper layer transition (climbing)	
$T_{t_i} = T_{a_i}$	for i=1
$T_{t_i} = T_{a_i} + T_{g_{i,i-1}}$	$\forall i > 1$
Vertical links: lower layer transitions (descent)	
$T_{t_i} = T_{f_i}$	for i=1
$T_{t_i} = T_{f_i} + T_{g_{i,i-1}}$	$\forall i > 1$
Headway time at the vertiport I_{N_F}	
$T_p = T_{r_{i-1}}^{h_{mL}} + (T_{a_i}^{v_{mL}} + T_{g_{(i,i-1)}}^{h_{mL}})$	
$I_{N_F} = T_p + T_{g_{(i,i-1)}}^{a_{mL}}$	if $i-1$ is ahead of destination node $N_{T,L}$
$I_{N_F} = T_p$	if $i-1$ is beyond destination node $N_{T,L}$

The computation of the link cost will be based on both offline and real-time data made available by V2V and V2I/V2X communication technologies. As a consequence, for scheduled services the shortest path is computed before FV departures, thus the UAN is used in a "steady state" mode, and minimum paths are identified in advance, depending on the expected points of conflict and number of flight operations [70]. Differently, for unscheduled (i.e., on-demand) services, information on the occupancy status of the dynamic links has to be shared in real time.

During the trip, if a dynamic link reaches its capacity limit, it will be "disabled" to guarantee safety standards, avoid traffic jams, and network disruptions. In this case the FVs will be redistributed over the network and their paths recomputed. In case of disruption on one or more links, the computation of new flight plans will be based on real time information similarly to unscheduled services. Moreover, FV route and departing slot assignment depends only on service scheduling. In particular, take-off and landing priority must match with both the time gap on the links and headway time at the fixed nodes, also adopting a see-and-avoid approach [80]. Finally, when a service integrates both on-demand and scheduled flights, the on-demand flight will be allowed if the time gap is sufficient.

3.2. The Freight Distribution Problem

The previously described 3D-UAN model is applied here to address the freight distribution problem. In particular, FVs are supposed to be employed for the transportation of goods between Urban Consolidation Centres (UCCs) –logistics facilities typically located near urban areas, where goods are collected and subsequently redistributed for last-mile delivery– illustrated in Fig. 1. Vertiports for landing/take-off are considered located close to or inside UCCs, so that in the following the terms vertiports and UCCs are considered interchangeable for the purpose of the 3D-UAN operating conditions, unless otherwise specified.

FVs operate along the arcs of the 3D-UAN following a pre-scheduled flight plan, while retaining the capability of autonomously adapting some flight parameters in response to contingent events, especially those arising from interactions with other FVs.

In detail, freight transfers between UCCs (Fig. 1) follow a planned schedule, which may be dynamically adjusted to meet real-time requirements. This introduces the need to update the initial flight plans of

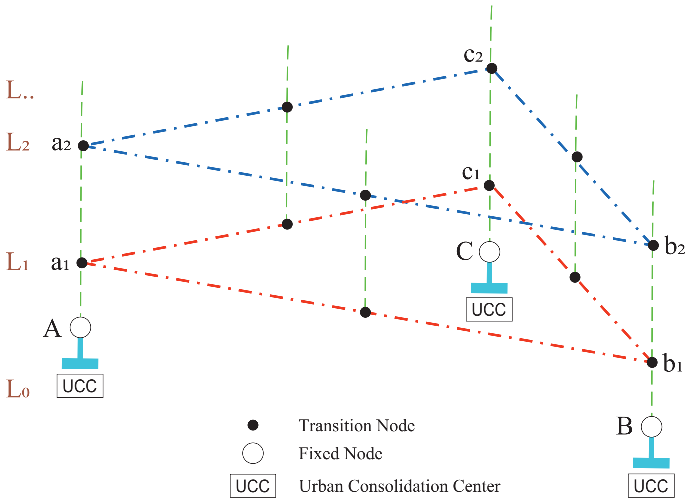

Figure 1: Scheme of a 3D-UAN for the freight distribution problem

the FVs accordingly. The use of the 3D-UAN architecture –specifically the aerial corridors represented by the sequence of links in the multi-layered network– is essential to ensure safe navigation within complex urban environments. In fact, although UCCs are generally located at the periphery of city centers, these areas are not entirely free from obstacles such as buildings or other anthropogenic and natural structures (e.g., antenna towers or high-voltage pylons), thus requiring a fixed network architecture that avoid obstacles for ensuring safe trips.

4. The 3D-UAN Agent-Based Architecture for the Freight Distribution Problem

Based on the 3D-UAN architecture described in the previous section, a distributed agent-based framework is introduced to model freight distribution scenarios for the last mile delivery problem.

In this framework, each operational entity –namely Flight Vehicles (FVs), Fixed Nodes (FNs), and the Air Traffic Control (ATC) center– is represented by a dedicated software agent, denoted as FV^A, FN^A, and ATC^A, respectively. Each agent autonomously manages its assigned tasks by evaluating alternative options based on predefined roles and competences. While there are as many agents as the number of FVs and FNs in the network, there is only one ATC, which has the role of authorizing and managing mobility services –e.g., in line with the HyperTwin platform developed within the project "Digital Twin for Innovative Air Services - DT4IAS" (https://hypertwin.enac.gov.it/).

Moreover, agents operate within a dedicated communication system, underpinned by an internal Agent Directory (AD) supporting the messaging infrastructure. Inter-agent coordination occurs through structured messages –following a simplified JADE-like format [81] containing metadata such as sender ID, receiver ID, message type, and content payload. Note that the framework assumes that all business and technical prerequisites are satisfied, thus ensuring full interoperability among the several components and enabling seamless operations.

In detail, for each trip between two or more vertiports, ATC^A receives, checks and assigns a flight plan to FV_i^A. Each FN_j –spatially corresponding to a UCC/vertiport– is associated with its agent FN_j^A, which oversees the airspace surrounding FN_j (along both horizontal and vertical directions), supervises take-off and landing operations, and exchanges data with other agents within a suitable communication range. In detail, each FN_j^A maintains up-to-date data on traffic flows in its forward and backward star (i.e., the set of inbound arcs), thereby enabling congestion checks and enforcement of arc capacity constraints.

Each FV_i^A follows a 3D path between UCCs consisting of sequences of links, whose endpoints may be fixed nodes or transition nodes, or both (see also Fig. 1). FV_i^A is responsible for monitoring the adherence to the defined flight plan as well as its necessary modifications, facilitating inter-agent communication (with nearby FV^As, FN^As, and ATC^A), and maintaining overall operational compliance.

Compared to an initial scheduled path transmitted to ATC^A, which checks for consistency among all the FV paths in the given reference time, during its trip FV_i^A can make changes on the basis of local information received by communicating with neighboring FV_k^A and with FN_j^A located at the nearest fixed node FN_j, ahead of FV_i^A route. Particularly, when passing at the initial node of a given link (h_m or v_m) belonging to its path, FV_i^A stores the information about the status of the next link. If such link is currently unavailable because it is at its capacity limit, FV_i^A will switch layer –i.e., vertical level– but only at the final node of its current link, which will correspond to a transition node. The information about the link capacity status is provided by the closer FN_j^A, which collects data referring to the transit of FV on the links belonging to both the forward and backward stars of FN_j^A itself. Note that the fixed node must be able to send and receive information within a suitable radius, covering at least twice the link length.

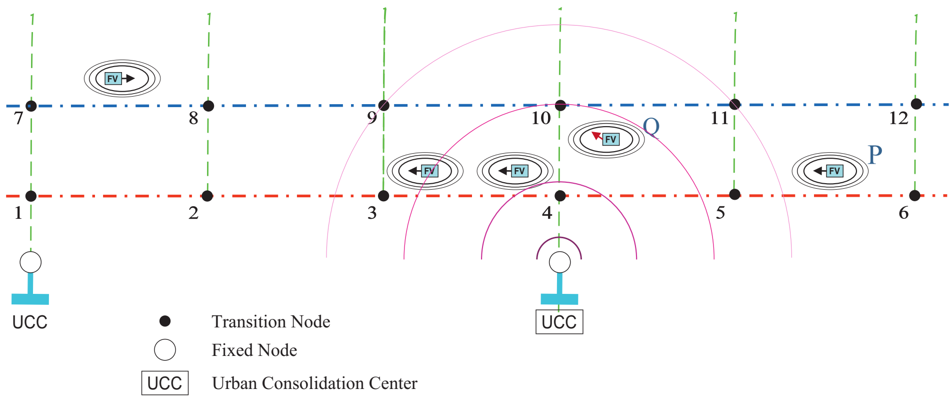

Figure 2: Path variations based on information exchanges

As an example, in Fig. 2, the FV 'P' is traveling along the link $6-5$, and receives information that link $4-3$ is at its capacity limit, while link $4-10$ is occupied by the FV 'Q' on its way up. Therefore, P recomputes its path by switching level along the link $5-11$ and send the information to FN_j^A, which in turn will send the information to the closest FN^As, so that the information chain through the several FN^As allows ATC^A to receive the information and update the flight plan of FV_i^A. ATC^A is responsible for maintaining real-time global awareness of the UAN, managing flight plans, and dynamically activating or deactivating air corridors in response to network load conditions. Particularly, after a path change ATC^A forwards the information to each FN_j^A. This ensures optimized and coordinated use of the shared airspace. At the same time, all the other moving FVs will receive information by their FV_i^A and by FN_j^A about the position of other agents and the status of the links they should use, so that the whole system cooperates following a distributed architecture.

5. Experiments

To test the architecture described in Section 4, a simulated freight distribution test case has been modeled on a 3-layer 3D-UAN that includes 3 UCCs. The links connecting the transition nodes have been considered equal for simplicity, but nothing would change for testing the architecture if different link lengths are associated with each link in the network. In fact, given the aerial nature of the 3D-UAN, the length of links connecting two transition nodes may be considered equal without lack of generality. In real cases, slight differences may arise for links connecting transition and fixed nodes (i.e., vertiports/UCCs), which correspond to ground-located points.

To set the value of the link length, some assumptions should be made about the features of the FV (in the following also called drone) considered in the experiment, particularly speed, range and autonomy.

Currently there are several prototypes whose speed ranges may vary significantly depending on factors such as the type of drone (multi-rotor vs. fixed-wing), the mass of the load being carried, the environmental conditions (wind, temperature), the mission profile (urban or rural, distance, altitude). Among the several drones currently available, the most suitable one for the freight transport is a hybrid VTOL type (fixed-wing + multi-rotor). In fact, vertical take-off and landing capabilities are useful for restricted urban areas, and the extended range covers the distances between UCC-city center and return. Good cruising speed and hovering stability for precise delivery complete its potentialities for this aim. Table 2 reports the main features of the FV considered in this experiment.

Table 2
FV features for freight distribution in urban and suburban areas.

Useful payload	320 kg (typical urban use)
Real operating range	$15 - 50$ km
Cruising speed	$80 - 120$ km/h
Take-off/landing speed	45 km/h
VTOL	Essential for operating in urban centers
Energy autonomy	At least 30 minutes for intermediate missions

As for the whole distance between UCCs, which are also playing the role of recharging points in addition to the one of vertiports for landing/take off, the constraint considered here for safety reasons is that such length must be less than or equal to the minimum value of the FV operating range. In addition, further considerations refer to the optimal distance between drones (associated to FV_i^A) and UCCs (associated with FN_j^A), and among drones for communication issues. Such distances depend on the used technology, and may range from 100 mt to $20,000$+ mt. Based on drone autonomy, communication ranges, and communication aims, the whole distance between UCCs has been set equal to 8 km, which is within the range of observed distance between UCCs in real cases. Referring to Fig. 1 as example the horizontal link lengths have been set equal to 2000 mt, while vertical link lengths have been set equal to 30 mt, which corresponds to a suitable safe distance between two next layers. With these assumptions, and the specified distance of $8,000$ mt between UCCs, the number of horizontal links is 12 per layer, the total number of horizontal links is 36, the number of transition nodes is 36 and the number of vertical links is 24 (see Table 3). Finally, it is worthwhile to note that the assumed vertical length, which also corresponds to the height at which drones can fly to deliver goods, depends on the specific regulations of each country, the technologies used and the presence of obstacles. However, there are general guidelines that apply globally, suggesting that flight height for cargo delivery drones is generally less than $120 - 150$ mt. [82, 83, 84].

Each FV operates based on a predefined flight plan, which –as outlined in Section 3.2– may be dynamically adjusted to ensure safety and efficiency. The movement along horizontal links is governed by directional constraints: two FVs must not simultaneously traverse the same link in opposing directions. Vertical dynamic links connect only adjacent layers.

Additionally, dedicated approach and departure zones are established in proximity to each vertiport to streamline vertical integration with flight layers and manage access to/from on-ground parking stands.

To ensure safety and maintain operational consistency, the average cruising speed is set to 100 km/h for horizontal movements and 45 km/h for vertical transitions, including take-off and landing procedures. Depending on the drone characteristics and related safety reasons (see Tables 2 and 3), a maximum of 2 FVs per time interval is assigned to each horizontal link and 1 FV for each vertical links. This constraint is derived from the link length and the predefined cruising speed of the FVs, and it is in line with the minimum recommended horizontal distance for two drones moving at 100 km/h, which is at least 100-150 meters to ensure that they can move safely and avoid collisions. Similarly, the minimum recommended vertical distance between two drones for moving goods delivery should be at least 10-20 meters to ensure safety, which again is in line with the assumed maximum number of FVs on vertical links.

Table 3
Network main characteristics.

Fixed nodes (UCC)	3
Transition nodes	36
Vertical links	24
Horizontal links	36
Distance between UCC	$8,000$ mt
Horizontal link length	2000 mt
Vertical link length	30 mt
Communication range between drones	$50 - 5,000$ mt
Communication ranges between drones and UCCs	$100 - 10,000$ mt

The simulation framework is based on the following assumptions: (*i*) Only in-flight travel time is considered; ground-related operations such as freight handling and security checks are excluded; (*ii*) All physical services are assumed to occur exclusively at vertiports; (*iii*) Stand availability at vertiports is limited—requests may be denied if no stand is available at the desired time, which can influence flight plan feasibility and routing decisions. It is worthwhile to note that this preliminary setting of the proposed framework does not explicitly consider latency and communication costs, which are considered here not influential, similarly to what has been assumed for travel costs (deterministic hypothesis). In other words, assuming no latency and scalability issues corresponds to consider an ideal situation, i.e. an optimal reference condition.

Table 4
Link operational features.

Maximum horizontal link capacity (number of FVs)	2
Maximum vertical link capacity (number of FVs)	1
Average cruise speed on horizontal links	100 km/h
Average cruise speed on vertical links	45 km/h

Simulations were conducted using the same numerical agent-based simulator described in [85, 86], developed in C++ and operating without a graphical user interface. To compute the travel times on each link, the cost functions introduced in Section 3 have been applied. The temporal gaps between two FVs, $T_{g_{i,i-1}}$, has been set equal to 40 sec, which guarantees suitable safe separation between them. The same algorithm is used to updated the original flight plan if changes are required. In this case, some additional information concerning the status of the network are also used, particularly if some links are enabled because of capacity constraints. Unrealistic paths and overlaps are excluded during the path search process, and only a limited number of layer transitions (both up and down) are allowed, in accordance with operational and energy constraints. At a first attempt, such number has been set equal to 2. Finally, 30 FVs are considered operational in the simulation period, traveling across 6 origin/destination pairs, i.e. the UCC pairs. They have been assigned to each pair following an initial scheduled plan, which has been modified during the simulation by introducing some randomness in the FV motion. Particularly, 30% of the FVs operating during the simulation period have been considered affected by some delays due to disturbances (such as wind conditions, delays at departure, loading procedures and so on), which introduces modifications in their original scheduled travel time and requires adjustments to the flight plans of other FVs.

The overall setup supported the calibration of the agent-based simulator and the fine-tuning of agent behaviors. It is important to note, however, that as demonstrated in [87], simulated urban characteristics –such as vertiport placement, city layout, building heights, and vertical obstacles– can significantly influence the outcomes of such simulations.

6. Results and implications.

To summarize the performances of the agent-based 3D-UAN architecture for the freight delivery problem, some indicators have been computed.

The first indicator, Average Aerial travel Time (AAT) refers to the total average time spent by the FV_js moving among the UCCs. It has been obtained by dividing the total travel time by the considered number of FVs. In addition, AAT has been computed with and without the simulated disturbances that generated delays in the scheduled flight plans, thus requiring flight plan adjustments during the trip (respectively, AATn and AATc). The second indicator compares the average travel times –with and without disturbances– with the Average Ground travel Time (AGT) of equivalent automated ground vehicles moving on the roads among the UCCs, where vehicle characteristics are defined in terms of average speed (50 km/h). Such speed value has to be considered as the average value between extra-urban and urban roads, these latter being affected by congestion issues that reduce the average speed value. The road network has been considered as the 2D projection of the 3D-UAN, where transition nodes have no longer such meaning but are simply intersections or singular points of road links. The link length has been assumed equal to the aerial corresponding link length. To keep coherence, the same cost functions for horizontal links and the same number of vehicles have been considered for the simulation.

Table 5
Comparison between aerial and ground average travel times.

Indicator	Value (min.)
ATTn	15.2
AATc	18.8
AGT	31.1

The results, reported in Table 5, suggest that FVs can reduce delivery time, as they can move faster by following straight lines, while ground vehicles are limited by traffic as assumed in the experiment where a limited average speed has been considered for including interference among ground vehicles. It is worthwhile to note that ground links have been assumed equal to the aerial, corresponding ones. This assumption might be considered an ideal condition for ground networks, because road links –particularly in extra or suburban contexts– are not equal. Particularly, aerial link length can be considered as the line-distance between two ground points and therefore such distance is generally shorter than the real ground distance. As a consequence, assuming road lengths equal to aerial link length represents a better condition than the real one, which has been deliberately assumed here in order to compare the best possible ground scenario with the aerial ones. Despite this favorable hypothesis for the ground system, the aerial freight delivery architecture still provides better results, both with and without disturbances. Therefore, drones seem to be potentially effective for delivering freight in short time, particularly if they operate in dense urban areas where ground traffic jams may reduce substantially ground vehicle speed.

Although the obtained results are in line with expectations, i.e. drones are expected to be faster in delivering freight at short-medium distances, however some further tests must be carried out to assess the effective potentialities of a 3D-UAN freight delivery system. In particular, aspects to be explored are the effects of battery consumption depending on the drone load capacity, which may affect the size of the fleet for ensuring a continuous and effective delivery service. However, increasing the fleet size has effects on the link capacity, which would increase headway times. In addition, increasing the fleet size would generate scalability issues, particularly exponential increase in communication traffic between agents and increasing computational burden for each drone. Furthermore, as the number of drones increases and/or the network complexity increases, the number of exchanged messages among drones increases too and therefore latency. With high latency, information arrives late and drone decisions could be based on out-of-date data, which increases collision risks and coordination instability. Such interactions require further research and experiments. Finally, another important aspects deserving further studies is setting an aerial-ground transport network model considering both aerial and ground legs for the freight delivery problem. In other words, last mile delivery - mainly in urban and sub-urban areas -seems the most suitable field of application of freight drones, but medium-long distance trips are still to be realized by existing ground (or sea depending on market locations) routes. Integrating aerial and ground networks has been explored in the literature –see for example the recent study by [88]– but mainly for passenger demand.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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