| Artículo de investigación | Research Article | Artigo de investigação |

Structuring The Urban Airspace For Efficient Logistics Traffic Operation

Fecha de recibido: 07 de junio 2023	Fecha de aprobado: 07 de septiembre 2023
Reception date: June 07, 2023	Approval date: September 07, 20233
Data de recebimento: 07 de junho de 2023	Data de aprovação: 07 de setembro de 2023

Bruno Lamiscarre
https://orcid.org/0000- 0002-0314-2800
bruno.lamiscarre@neometsys.fr
Master of Science
Researcher and teacher – Cape Peninsula University of Technology (CPUT), France
Researcher's role: Theoretician
Research group: Department of Electrical Engineering
Magíster en Ciencias
Investigador y docente – Universidad Tecnológica de la Península del Cabo (CPUT), Francia
Rol de investigador: Teórico
Grupo de investigación: Departamento de Ingeniería Eléctrica

Innocent E. Davidson
https://orcid.org/0000-0002-2336-4136
davidsoni@cput.ac.za
Doctor of Philosophy (Ph.D.) in Electrical Engineering
Researcher and teacher – Cape Peninsula University of Technology (CPUT), South Africa
Researcher's role: Theoretician
Research group: French-South African Institute of Technology (F'SATI) / African Space Innovation Centre (ASIC)
Doctor en Ingeniería Eléctrica
Investigador y docente – Universidad Tecnológica de la Península del Cabo (CPUT), Sudáfrica
Rol de investigador: Teórico
Grupo de investigación: Instituto Tecnológico Franco-Sudafricano (F'SATI) / Centro Africano de Innovación Espacial (ASIC)

Yeisson Rincón Cuta
https://orcid.org/0000-0002-5086-3985
yeisson.rinconc@epfac.edu.co
Master's degree in integrated management systems for occupational risk prevention, quality, environment and corporate social responsibility
Researcher and teacher – Colombian Aerospace Force Postgraduate School, Colombia
Researcher's role: Theoretician
Logistics and Administration Research Group (GILOGA)
Magíster en sistemas integrados de gestión de prevención de riesgos laborales, calidad, medio ambiente y responsabilidad social corporativa
Investigador y docente – Escuela de Postgrados de la Fuerza Aeroespacial Colombiana, Colombia
Rol del investigador: Teórico
Grupo de Investigación en Logística y Administración (GILOGA)

Luis Gustavo Zelaya Cruz
https://orcid.org/0000-0002-4272-4643
lgustavozelaya@gmail.com
Doctor en Ingeniería Industrial
Researcher and teacher – Fluminense Federal University (UFF), Brazil
Researcher's role: Theoretician
Doctor en Ingeniería Industrial
Investigador y profesor – Universidad Federal Fluminense (UFF), Brasil
Rol de investigador: Teórico

Felix Mora-Camino
https://orcid.org/0000-0003-1930-6125
moracamino@hotmail.fr
Doctor of Science
Researcher and teacher – Fluminense Federal University (UFF), Brazil
Researcher's role: Theoretician
Research group: ACAM Aran Center for Applied Mathematics
Doctor en Ciencias
Investigador y docente – Universidad Federal Fluminense (UFF), Brasil
Rol del investigador: Teórico
Grupo de investigación: ACAM Centro Aranés de Matemática Aplicada

Cómo citar este artículo: Lamiscarre, B., Davidson, I.E., Rincón Cuta, Y., Zelaya Cruz, L. G., & Mora-Camino, F. (2024). Structuring The Urban Airspace for Efficient Logistics Traffic Operation. Ciencia y Poder Aéreo, 19(1), 24-31. https://doi.org/10.18667/cienciaypoderaereo.799

Structuring The Urban Airspace For Efficient Logistics Traffic Operation

Abstract: This paper considers the problem of structuring the urban airspace so that UAVs-based-urban-logistics can be performed efficiently. This problem is important to guarantee mobility and accessibility for all operators. First, a set of assumptions about the organization of the lower layers of the urban airspace is proposed, then an optimal flow assignment problem is formulated, a heuristic solution approach is developed and, finally, its application to a medium size problem is displayed.

Keywords: UAVs; logistics; urban airspace; air traffi management; networks; optimization and heuristics.

Estructuración del espacio aéreo urbano para un funcionamiento eficaz del tráfico logístico

Resumen: este trabajo considera el problema de la estructuración del espacio aéreo urbano para que la logística urbana basada en UAVs pueda realizarse de forma eficiente. Este problema es importante para garantizar la movilidad y accesibilidad de todos los operadores. En primer lugar, se propone un conjunto de hipótesis sobre la organización de las capas inferiores del espacio aéreo urbano, a continuación se formula un problema de asignación óptima de flujos, se desarrolla un enfoque heurístico de solución y, por último, se muestra su aplicación a un problema de tamaño medio.

Palabras clave: UAVs; logística; espacio aéreo urbano; gestión del tráfico aéreo; redes; optimización y heurística.

Estruturação do espaço aéreo urbano para uma operação eficiente do tráfego logístico

Resumo: Este artigo considera o problema da estruturação do espaço aéreo urbano para que a logística urbana baseada em VANTs possa ser realizada de forma eficiente. Esse problema é importante para garantir a mobilidade e a acessibilidade de todos os operadores. Primeiro, é proposto um conjunto de suposições sobre a organização das camadas inferiores do espaço aéreo urbano, depois é formulado um problema de atribuição de fluxo ideal, é desenvolvida uma abordagem de solução heurística e, por fim, é apresentada sua aplicação a um problema de médio porte.

Palavras-chave: UAVs; logística; espaço aéreo urbano; gerenciamento de tráfego aéreo; redes; otimização e heurística.

Introduction

UAV networks have been considered in the recent literature and are mainly related to either mobile communication networks, based on fleets of UAVs or with route generation for delivery services with UAVs. Important perspectives for the development of urban logistics based on the operation of UAVs have been consolidating, according to recent publications (Sah et al., 2021; Eun et al., 2019; Goodchild & Toy, 2018; Park et al., 2018; Koiwanit, 2018). These perspectives will be able to profit from the until now unused urban airspace to the then alleviate ground traffic by diminishing the needs for ground-based logistic transportation, which is one of the main contributors to ground urban traffic congestion and pollution.

Previously, many studies have been devoted to the design of efficient UAVs based-urban-logistics systems (Roca-Riu & Menendez, 2019; Iranmanesh et al., 2020; Zubin et al., 2020), where, in general, traffic volumes and capacities are not taken as issues. However, Doole et al. (2018) show that, in few decades, the expected high traffic of drones operating in the urban airspace will make imperative its effective organization to turn feasible air traffic management. Structuring the airspace and adopting systematic procedures to operate this structured airspace will provide *ad-hoc* solutions for urban logistics air traffic operations (EmbraerX et al., n.d.). Then, the Air Traffic Management (EmbraerX, 2019) will be mainly in charge of flow management and dynamic airspace management.

In this study, the development of a method to structure the considered layer through the definition of a network of air links to operate traffic flows of UAVs devoted to general logistics in an urban area. This is considered through the resolution of the assignment of expected demand along feasible paths.

The paper is organized as follows: First, assumptions about operational objectives for UAVs-based-logistics in the urban airspace are proposed, leading to a structuring proposal for the lower layer of the urban airspace. Then, the optimization problem of the operated network inside the urban airspace is formulated and a heuristic solution approach is developed and illustrated. Finally, the usefulness of this tool for Air Traffic Management is discussed.

Basic assumptions and definitions

A basic assumption of this study is that urban logistic air traffic operates over the ground links of the considered urban area (avenues, streets and squares), while the urban passenger traffic is performed between the top of buildings (public and private) and open areas such as parks, cemeteries and outdoor parking areas. Then, it is considered that urban passenger air traffic is completely segregated from logistics air traffic, avoiding collision risks with those UAVs devoted to logistics. The urban area is supposed to be subdivided in subareas for which estimated or online origin-destination demand data is available. The considered air traffic flows are either local flows within a subarea or flows between subareas. A gate-to-gate flight between different subareas will present also an initial and a final local part.

The decision problem considered in this study is relative to the design of the urban airspace devoted to logistics flights between different subareas. This design is materialized through network linking reference points of the different subareas of the urban space. Once the network has been defined, users demand for air mobility will be assigned to paths belonging to this frame.

While designing this network, the main considered design objectives are to ensure mobility, accessibility and safety, master traffic safety, network capacity, and environmental impacts. The main constraints to be taken into consideration are the following:

- The designed network should provide reachability for any origin-destination pair associated with a demand for logistic UAVs services between subareas.

- The designed network is a capacitated network where each link is characterized by its length and capacity. This capacity is the maximum flow per unit of time compatible with a safety and local environmental impact.

As demand evolves in the short term (from one hour to another), the proposed solution must be easily adaptable to new demand profiles.

Let's then define the following sets, variables and parameters:

- O, the set of origins, and D, the set of destinations, with in general $|O| \ll |D|$.
- G: the oriented graph linking origins and destinations;
- C_{hl}: the maximum air traffic allowed in airlink (h,l) during the considered period;
- D_{ij}: the flight demand for airborne logistics between origin i and destination j during the considered period.

Analysis of candidate problem formulations

The objective here is to determine which links will be used to realize the expected airborne logistics and what will be their intensity, considering some practical capacity attached to each candidate link. For this, a flow optimization problem is considered where the goal is to minimize the overall travelled distance while performing the airborne logistics operation. The considered problem presents specific characteristics when compared to traditional urban ground transportation network design problems or when it refers to air transportation network design problems, so new solution approaches should be developed.

The overall capacity C_G of the considered network can be computed using some of Ford & Fulkerson's scheme (1956) once a global source is connected to all the origins and a global sink is connected from all the destinations, both with infinite capacity links. A necessary condition for the feasibility of the flow assignment problem is that:

$$\Sigma_{i \in O} \Sigma_{i \in D} D_{ij} \leq C_G \quad (1)$$

A linear programming minimum cost flow problem can be easily formulated considering the minimization of total travelled distance under restrictions of positiveness, origin, destination, flow conservation, and capacity restrictions. However, when referring to the task of the traffic manager and the adopted point to point logistics operation, the decision variables are the paths adopted between each origin destination pair and their frequency. Then traffic flows in the urban network are the result of these traffic management decisions.

Taking as a basis the underlying street network and its local characteristics (overflight authorized or not), for each origin-destination pair a reduced set of possible air-paths linking them can be defined. Here it is also supposed that in a round trip the same path is used in reverse to come back to the origin of the flight.

The path flowbased-formulation of the design problem associated to the routing and capacity airspace management function of the Air Traffic Manager results in the following optimization problem:

$$min\, \Sigma_{i \in O} \Sigma_{j \in D} \Sigma_{k \in P^k_{ij}} L^k_{ij} \cdot X^k_{ij} \quad (2)$$

under the constraints of capacity of the candidate elementary airlinks:

$$\Sigma_{i \in O} \Sigma_{j \in D} \Sigma_{k \in P^k_{ij}} a^{khl}_{ij} \cdot X^k_{ij} \leq C_{h,l} \quad \forall (h,l), h \neq l \quad (3)$$

and

$$\Sigma_{k \in Pij} X^k_{ij} = D_{ij} \quad \forall i,j, i \in O, j \in D \quad (4)$$

with

$$X^k_{ij} \geq 0 \quad k \in P^k_{ij}, \quad \forall i,j, i \in O, j \in D \quad (5)$$

where:

- P^k_{ij} is the set of the K best elementary paths linking the origin i and the destination j in the air logistic network of graph, where K is a small integer number;

- U^k_{ij} is the set of elementary airlinks composing the k^{th} path between origin i and destination j;
- L^k_{ij} is the length of the k^{th} path between origin i and destination j:

$$L^k_{ij} = \Sigma_{(h,l)\epsilon U^k_{ij}} \; L_{hl} \tag{6}$$

where L_{hl} is the length of airlink (h,l);

- $[a^{khl}_{ij}]$ is the incidence matrix between the k^{th} path between pair (i, j) and airlink (h,l): $a^{khl}_{ij} = 1$ if airlink (h,l) belongs to the k^{th} path between origin i and destination j, otherwise, $a^{khl}_{ij} = 0$;

Here the total flown length is minimized (relation (2)) under capacity constraints (relation 3) for all the candidate elementary airlinks, constraint (4) insures that demands between pairs i, j are satisfied and constraints (5) recall the positive nature of the considered decision variables.

Then, if a solution is obtained, those links composing a used path (path k^* between i and j when $x^{k*}_{ij} > 0$) will be retained for proper equipment in the air logistic network. When no solution is available, constraints (3) can be relaxed to allow a limited number of multiple paths while demand must be assigned to several paths. This will be part of the flow management function of the Air Traffic Manager.

To produce acceptable solutions to the above linear network optimization problem, a greedy heuristic solution approach has been developed and its application to a medium size problem is considered.

The above formulation assumes that the K shortest paths problem has been solved for each pair of origin and destination. This can be performed using a generalization of Dijsktra's algorithm (Yen, 1971), while Yen's algorithm produces the K shortest loop less paths [14]. The complexity of such algorithms is polynomial, but in practice they lead to a very large amount of computation and memory space. Another limitation of this approach is that it is a static formulation whose solution does not provide hints for the management of the dynamic loading process of the network.

Proposed heuristic solution approach

A different approach avoiding this calculation is developed here. The main ideas are to favor the most direct paths for each origin destination pair through a progressive loading of the network which can provide the dynamic routing policy of the Air Traffic network Management. The proposed approach is composed of the following steps:

0) Set $\delta_{ij} = D_{ij}\, x_{ij} = 0\ \forall i, j, i \in O, j \in D, L_{min} = 0$, the initial decision space is the original network (the directed graph with its link capacities).
1) Use an algorithm such as Dijkstra's to compute the minimum paths between each origin and each destination with a nonzero demand in the current graph decision space. If there is no path between an origin and a destination, the corresponding demand for service δ_{ij} cannot be fulfilled and must be deleted from the formulation. This residual demand could be processed through a ground transportation mode.
2) Compute the incidence matrix of the minimum path linking pair (i, j) and airlink (h,l), $[a^{1hl}_{ij}]$, as well as the length of each minimum path L^1_{ij} in the current decision space.
3) Assign the current demand $[\delta_{ij}]$to the minimum length paths between each origin and destination pair.
4) Compute for each origin i destination j pair and the load factor L_{ij} defined as follows:

$$_{ij} = C_{hl}/(\Sigma_{\alpha\epsilon O} \; \Sigma_{\beta\epsilon D} \; a^{1hl}_{\alpha\beta}\,\delta_{\alpha\beta} \tag{6}$$

   a. If $L_{ij} \geq 1$ the current solution for the origin i destination j pair is given by:

$$x_{ij} = x_{ij} + \delta_{ij} \tag{7}$$

is feasible and the overall performance is updated by:

$$L_{min} = L_{min} + L^1_{ij} \cdot \delta_{ij} \tag{8}$$

b. If L_{ij}< 1 that means that the capacities of some arcs in the current path between origin *i* and destination *j* are exceeded: only $_{ij}\ \delta_{ij}$ is assigned to this path;

5) Coming back to the whole network:

a. The newly saturated arcs (*h*, *l*) of the network such as $\Sigma_{i\epsilon O}\ \Sigma_{j\epsilon D}\ a_{ij}^{1hl}\ _{ij}\ \delta_{ij}$ = $C_{h,l}$ are removed from the graph of the decision space;

b. The capacities of the remaining arcs are updated:

$$C_{h,l} \leftarrow C_{h,l} - \Sigma_{i\epsilon O}\ \Sigma_{j\epsilon D}\ a_{ij}^{1hl}\ \ _{ij}\delta_{ij} \qquad (9)$$

c. The residual demand is computed for each origin destination pair:

$$\delta_{ij} \leftarrow \delta_{ij}\,(1 - \ \ _{ij}),\ \forall i,j,\ i \in O, j \in D \qquad (10)$$

6) Go back to step 1.

Observe that the convergence of the algorithm towards a global or a partial (part of demand is deleted by the lack of a path between the corresponding origins and destinations) feasible solution is trivial. The algorithm ends when no residual demand remains. The computation burden, even for very large networks, is rather reduced since at each iteration the more demanding effort is to compute a minimum path for each residual demand over a reduced network without considering effectively the values of the remaining strictly positive capacities of the links.

Illustration of the proposed approach

Figure 1 gives a scale representation of a considered network with two origins and four destinations, where the number associated to the twenty four two-ways links are the capacities.

Arcs with both extremities part of {a, b, c, d, e, f} have a capacity of 20, while all other arcs have a capacity of 40. Total demand is displayed in Table 1.

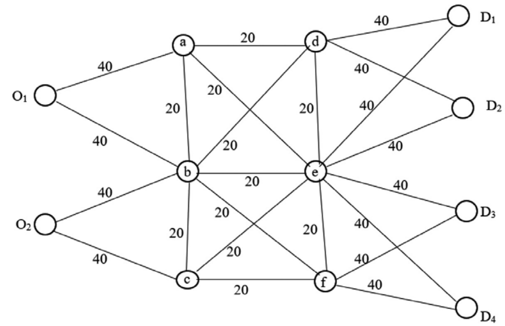

Figure 1. The considered logistic network

Table 1
Distribution of initial demand

	D_1	D_2	D_3	D_4
O_1	10	20	20	10
O_2	10	10	10	10

Observe that the min cut methods lead to a network capacity of 140, which is superior to 100, the total of demands. The first iteration of the algorithm provides the results displayed in Table 2 with the reduced available network of Figure 2.

Table 2
First assignment of flows to paths

Shortest paths	Path flow	Length	λ_{ij}	X_{ij}	δ_{ij}
O_1-a-d-D_1	10	3	2/3	20/3	10/3
O_1-a-d-D_2	20	3	2/3	40/3	20/3
O_1-b-e-D_3	20	4	2/3	40/3	20/3
O_1-b-f-D_4	10	4	2	10	0
O_2-b-d-D_1	10	4	1	10	0
O_2-b-e-D_2	10	3	2/3	20/3	10/3
O_2-c-f-D_3	10	3	1	10	0
O_2-c-f-D_4	10	4	1	10	0

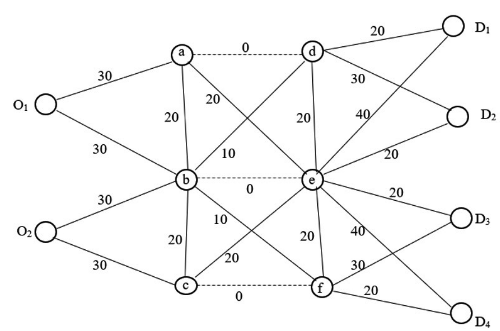

Figure 2. The reduced logistic network

The second iteration of the algorithm provides the results displayed in Table 3 with the residual network of Figure 3.

Table 3.
Second assignment of flows to paths

Shortest paths	Path flow	Length	λ_{ij}	X_{ij}	δ_{ij}
O_1-b-d-D_1	10/3	5	3	10/3	0
O_1-a-e-D_2	20/3	5	3/2	20/3	0
O_1-a-e-D_3	20/3	5	3/2	20/3	0
O_2-c-e-D_2	10/3	5	6	10/3	0

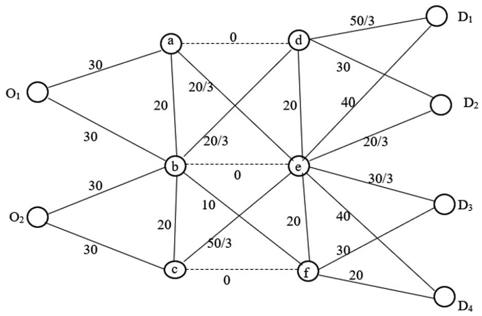

Figure 3. The final reduced logistic network

To the proposed solution corresponds a total round-trip distance of nine hundred with a mean distance of nine distributed over twelve different paths using a total of seventeen links over twenty-four. Observe the final reduced logistic network presents still a total flow capacity of 40.

A simple rule here to assign new incoming traffic in the logistic network during a considered period of time will be to distribute it among the generated paths proportionally to the computed flows provided by the proposed heuristic. For example, 2/3 of traffic between O_1 and D_1 will use path O_1-a-d-D_2 and 1/3 of traffic between O_1 and D_1 will use path O_1-b-d-D_1.

Conclusion

In this study, the prediction of the distribution of UAVs flows devoted to general logistics in the urban airspace has been considered. The objective has been to allow more direct flights for the logistics operators, as well as to limit the impact of this traffic over the surrounding population. The limitation of this impact is effective by considering at the same time practical flow capacities for the candidate air links and by concentrating these flows in a reduced number of air links along minimum length paths between origin and destination pairs. The proposed heuristic strongly reduces the computational burden generally associated to flows assignment problems and allows to tackle very large-scale logistics networks. The quality of the solutions will depend on the accuracy of the prediction of demand between origins and destinations, as well as on the link capacity settings of the quality of the air. The implementation of the proposed solution is eased by the definition of the paths to be followed between each origin-destination pair and the distribution of traffic between these paths. Future work will extend this approach to consider more directly air traffic conflict limitations specially at intersections.

References

Doole, M., Ellerbroek, J. & Hoekstra J. (2018). Drone Delivery. Urban airspace traffic density estimation. *Eighth SESAR Innovation Days.* https://pure.tudelft.nl/ws/portalfiles/portal/68971371/SIDs_2018_paper_3.pdf

EmbraerX. (2019, June 2nd). *Procedures will be key for Urban Air Traffic Management*. Vertical. https://evtol.com/news/embraerx-procedures-will-be-key-for-urban-air-traffic-management/

EmbraerX, Atech & Harris. (n.d.) *Flight Plan 2030. An air traffic management concept for urban air mobility*. https://daflwcl3bnxyt.cloudfront.net/m/4e5924f5de45fd3a/original/190527-whitepaper-flightplan2030-150dpi_.pdf

Eun J., Song B. D., Lee S. & Lim D. E. (2019)). Mathematical Investigation on the Sustainability of UAV Logistics. *Sustainability*, *MDPI, 11*(21), 1-15.

Ford, L. R. & Fulkerson, D. R. (1956). Maximal flow through a network, *Canadian Journal of Mathematics, 8*, 399–404.

Goodchild, J. A. & Toy, A. (2018). Delivery by drone: An evaluation of unmanned aerial vehicle technology in reducing

CO2 emissions in the delivery service industry. *Transportation Research Part D: Transport and Environment, 61*(A), 58-67.

Iranmanesh, S., Raad, R., Raheel, M., Tubbal, F. & Jan, T. (2020). Novel DTN Mobility-Driven Routing in Autonomous Drone Logistics Networks. *IEEE Access, 8*(1), 13661-13673. 10.1109/ACCESS.2019.2959275

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

Park, J., Kim, S. & Suh, K. (2018). A Comparative Analysis of the Environmental Benefits of Drone-Based Delivery Services in Urban and Rural Areas. *Sustainability*, *10*(3), 888.

Roca-Riu, M. & Menendez M. (2019, May 15 – 17). Logistic deliveries with Drones. State of the art of practice and research. *STRC, Swiss Transport Research Conference*, Monte Veritá, Ascona, https://www.strc.ch/2019/RocaRiu_Menendez.pdf

Sah, B., Gupta, R. & Bani-Hani, D. (2021). Analysis of barriers to implement drone logistics. *International Journal of Logistics Research and Applications*, *24*(6), 531-550. 10.1080/13675567.2020.1782862

Yen, J. Y. (1971). Finding the k-Shortest Loop Less Paths in a Network. *Management Science, 17*(11), 712–716.

Zubin, I., van Arem, B., Wiegmans, B. & Van Duin, R. (2020). Using Drones in the Last-Mile Logistics Processes of Medical Product Delivery: A Feasible Case in Rotterdam. *Proceedings of the 99th Annual Meeting TRB*, 1-17.

Escuela de Postgrados de la **Fuerza Aeroespacial Colombiana**