Unveiling the airspace structure and aircraft mobility in Europe: a complex network perspective

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Air transport constitutes a key socio-technical infrastructure of our society in terms of mobility. When it comes to modelling it, the most common representation is that of airport networks; that is, nodes correspond to airports pairwise connected whenever flights exist between them. However, flights do not necessarily follow a geodesic path between two airports; instead, they are restricted to fly following certain airways or pre-defined routes. This route networked structure constitutes the backbone of airspace, serving as the primary channel for aircraft flow.

In this contribution, we analysed an extensive dataset from EUROCONTROL's Data Archive [2], focusing on the European route structure and its evolution between 2015 and 2019. These routes are constituted by sequences of waypoints, navigational markers whose function is to guide aircraft on the right track. Fig. 1 displays a piece of this route structure in the Iberian Peninsula, revealing a higher density of waypoints near the major airports. Overall, the European route network encompasses more than 17,000 nodes and 31,000 edges.

While usually perceived as an almost static entity, the results reveal a highly dynamic structure. Notably, the network undergoes significant topological changes and experiences a remarkable increase in size of approximately 28% over the period from 2015 to 2019. A more in-depth discussion about the network's topological characteristics, evolution and spatial vulnerability can be found in [1].

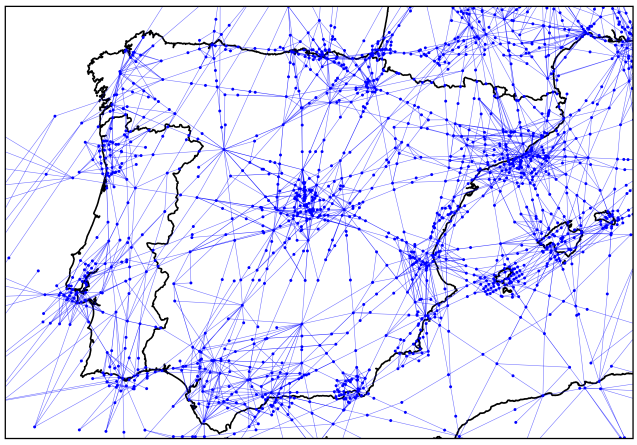

Fig. 1. Route structure of the Iberian Peninsula. Nodes correspond to waypoints, navigational markers used to guide aircraft; airways are formed as sequences of waypoints.

Before departure, each flight is required to provide its flight plan, which outlines the sequence of waypoints the aircraft is expected to follow. While the flight plan acts as a reference for actual trajectories, there is a certain degree of flexibility that allows deviations from the plan. These deviations are commonly referred to as *directs* in air traffic management. Directs occur when an air traffic controller instructs an aircraft to bypass one or more waypoints and proceed directly to the subsequent waypoint, minimizing flight distance and fuel consumption.

By integrating the route network with spatiotemporal flight trajectories, we can analyze the average number of directs taken per trajectory, as illustrated in Fig. 2. We observe a quite heterogeneous spatial distribution, with the FIR region of Riga standing out as particularly flexible, followed by Madrid, Milan, and Barcelona, regions known for managing a huge amount of traffic. To sum up, the present framework allows us to effectively characterize the flow of aircraft through the airspace and quantify actual flight deviations, offering valuable insights for air traffic management.

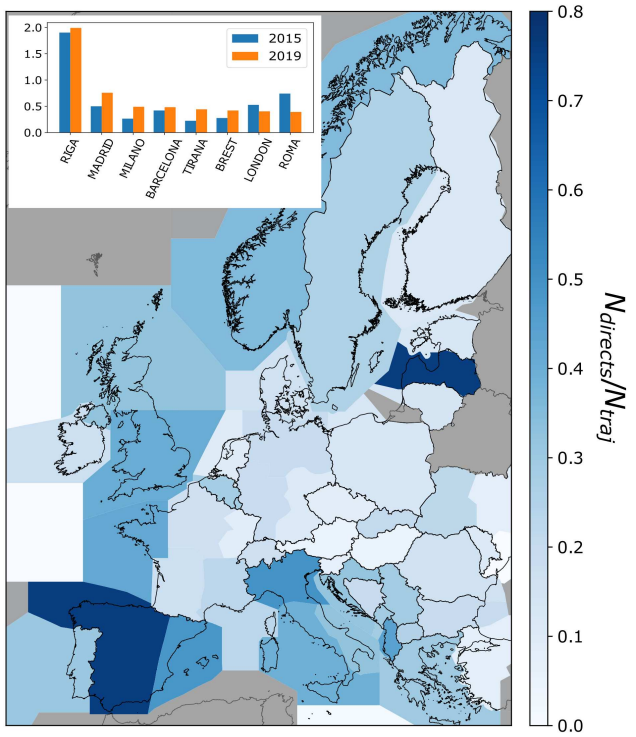

Fig. 2. Spatial distribution of the average number of directs taken per trajectory in 2019. The map is divided into the different Flight Information Regions (FIR) of the European airspace. The inset highlights the top 8 regions exhibiting a higher number of directs per trajectory, allowing a comparison of data between 2015 and 2019.

[1] P. Esteve, J.J. Ramasco, and M. Zanin, *Structure, resilience and evolution of the European Air Route Network from 2015 to 2018*, IEEE Transactions on Network Science and Engineering, 2023.

[2] https://www.eurocontrol.int/dashboard/rnd-data-archive