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Reachability for airline networks: fast algorithm for shortest path problem with time windows

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A B S T R A C T

Airline network, including airports as network nodes and flight routes as directed network edges, has a lot of special features such as departure and arrival times, air ticket budget, flight capacity, transportation cost, etc. Thus, analyzing network behavior and service performance for such a network is much more difficult than that for many other networks. In this paper, taking China domestic airline network as a representative, we try to discuss the reachability issue for each airport respectively, which could reflect its regional connectivity level and service quality of civil aviation. More specifically, we evaluate reachability through many features including node degree, betweenness, closeness, etc. To get the values of some features, we design a fast Dijkstra-based all-pair shortest path algorithm with both time and budget requirements, then use Fenwick Tree to further improve the time efficiency. Actually, it is a shortest path problem with time windows and other constraints. Furthermore, we propose a faster solution by reducing the edges in the duplicated graph as a simplification and then provide the time complexity proof. Finally, we implement Analytic Hierarchy Process (AHP) to convert the reachability feature into numerical values for all airports to measure their service qualities precisely. Our results for China domestic airline network with 210 airports and 69,160 flight routes will definitely become a guide to airline companies and civil aviation administration for their further development and management.

1. Introduction

Reachability and connectivity have been widely used as a measure to evaluate the networks and for graph there are also many widely used features to benchmark. However, when it now comes to the airline network, things will change. We consider an airline network as a graph including airports as nodes and flight routes as directed edges, which has a lot of differences from other networks. For instance, the graph may have hundreds or even thousands of parallel edges. Every edge in the graph has its own time window, which corresponds to the departure and arrival time of the flight route, and only in the time window can the edge be valid. What's more, every node has its specific values such as ground transportation

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cost, which makes all nodes essentially different. Since an airline network is a graph with a lot of distinctive features, it can hardly be measured in accordance with one or more explicit numerical indicators.

In this paper, we introduce a new definition of reachability, which is closely related to centrality and capacity. Centrality identifies how influential and important the node is in the graph, indicating the level of the corresponding airport. Capacity identifies the own value of the node itself regardless of the form of the graph. When it comes to centrality, we mainly consider degree centrality, betweenness centrality, and closeness centrality with time and budget requirements. For capacity, we consider flight frequency, seating capacity, and flight duration as auxiliary features. Then taking China airline network as a representative, we try to compute the reachability issue for each airport respectively through Analytic Hierarchy Process (AHP), which could indicate its rationality and superiority and be a guide to service improvement.

To figure out all the feature values, we design an algorithm to calculate the betweenness and closeness centrality, which is the most complicated part. There has been a fast algorithms for betweenness centrality [1], requiring $O(n+m)$ space and running in $O(nm+n^2\log n)$ on a weighted graph. However as is stated above, airline network is a network with many realistic features, so we should compromise to some realistic constraints. Actually, it is a shortest path problem with time windows and other constraints. To solve this problem, we presume the time of transfers is at most 7 and the total journey will take the passenger at most 7 days, otherwise the journey is hardly seen in the realistic world. To meet the two demands, we convert the original graph to a new three-dimensional graph, of which the three ordinates denote the airport, the time of transfers and the time of that moment respectively. After adding the corresponding edges to the new graph, we use Dijkstra algorithm with min-priority queue [1] to solve the all-pair shortest path problem. Considering some unnecessary cases, we use Fenwick Tree to reduce the size of the states, which seemingly makes the time complexity worse but actually accelerate it a lot. Additionally, we construct another duplicated graph with less edges generated comparing to the duplicated graph and implement the simplest shortest path algorithm to provide a better solution.

To summarize, in this paper we present a novel way to measure the reachability issue of an airport in airline networks. Taking China Airline Network as a representative, we define eight features for evaluation, and use Analytic Hierarchy Process (AHP) with expert grading matrix to quantitatively evaluate the reachability of airports. We further design a fast detection method using Dijkstra-based algorithm with a min-priority queue and Fenwick tree to calculate the betweenness and closeness features in this network. Our results for China domestic airline network with 210 airports and 69,160 flight routes will definitely become a guide to airline companies and civil aviation administration.

The rest of this paper is organized as follows: Section 2 summarizes the related works in this area. Section 3 introduces the definitions and requirements of the problem. Section 4 designs a fast algorithm to detect the betweenness and closeness centrality. Section 5 refines the previous algorithm by constructing another duplicated graph with less edges. Section 6 discusses the rating procedure to evaluate the reachability issue of an airport. Finally, Section 7 gives the conclusion.

2. Related work

As for airline networks, Barros et al. [2] used DEA two-stage procedure to evaluate operational performance of European airlines, considering number of employees, number of planes and operational cost; Tsaur et al. [3] evaluated airline service quality by fuzzy MCDM considering tangibility, reliability, responsiveness, assurance and empathy; Yu et al. [4] used the SBM-NDEA model to assess the performance of airports considering the airside service and landside service; Bowenet al. [5] used Airline Quality Rating (AQR) Methodology to evaluate the US airline industry. Although most of these researches considered many factors of airline networks, surprisingly few of them took complex network theory into consideration.

As for centrality, Brandes et al. [1] designed a fast algorithm for betweenness centrality requiring $O(n+m)$ space and running in $O(nm+n^2\log n)$ time on weighted networks; Kourtellis et al. [6] proposed a randomized algorithm for estimating betweenness centrality to identify nodes with high betweenness centrality; Lee et al. [7] constructed tourism-management strategies for villages by evaluating spatial centrality; Guimera et al. [8] claimed that nodes with high betweenness tend to play a more important role than those with high degree in the world-wide airport network. All of their work inspire us a lot, but we still need to tackle the centrality in such a complex network by ourselves.

As for the shortest path problem with time windows, some related works had time constraints on vertices but not edges. Moungla et al. [9] gave a dynamic programming algorithm to solve shortest path with regular time windows like $[a_i, b_i]$ which means the vertex can only be visited between a_i and b_i; Zhang et al. [10] gave an algorithm to solve shortest path with left-side time windows only. There are also some related works had time constraints on edges/paths. Chen et al. [11] proposed the MTT algorithm to solve time-constrained shortest path problem, and they assumed that there is no multiple arc, but our graph does have multiple edges between pairwise vertices; Ahuja et al. [12] proposed an algorithm to solve the minimum cost-path problems in street networks with periodic traffic lights. The fact that vehicles can pass intersections only when the traffic lights are green can be regarded as paths with time windows. After that, Androutsopoulos et al. [13] improved the solution to tackle a more general condition, and further gave their solution to solve the k-shortest path problem with time windows; Hu et al. [14] gave a better solution for the same problem recently. However, in our problem, which is in a more general and realistic condition, we should not only consider the least time period but also the least budget. That is a problem most of literatures not discussing about.

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