Pruning for the 'QPPTW' airport ground movement algorithm

Extended Abstract

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From a timetabling and scheduling of aircraft point of view, there are three main airport problems which are considered: allocating aircraft to gates/stands [5] (a resource allocation problem, allocating time on the limited stand/gate resources to the aircraft that need them); scheduling the use of the runway [4] (determining a time at which each aircraft will utilise the runway); and the ground movement problem [2] (efficiently moving the aircraft between their allocated gates/stands and runways). This work considers the problem of providing to controllers at an airport a decision support system which is fast enough to help them to tackle the last of these problems: deciding how aircraft should move around the airport.

Although approaches have in the past considered ground movement in the solutions to the stand allocation problem [8] and to the runway sequencing problem [1], it is common for the ground movement problem to assume that one or both of these problems has already been solved. In such a formulation, arrivals will often have a fixed (predicted) landing time, and the departures will have some earliest time at which they will be ready to leave the gate/stand, and potentially a planned take-off time for the runway. The problem is then to

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ensure that departing aircraft reach the runway in time to achieve any planned take-off sequence, and that landing aircraft traverse the airport to arrive at their allocated stands as soon as possible.

Since runway sequencing can be very sensitive to slight changes in timings, and aircraft will not always be ready exactly when predicted, the ground movement problem often has to be solved not long before aircraft movement would commence (once accurate timing information is available), and constantly re-solved as circumstances change. This means that the solution time for this problem is extremely important, and an answer may be required virtually instantaneously if any system is to be acceptable for live use at airports.

The ground movement problem is often modelled as the problem of routing aircraft around a directed graph from source to destination vertices, with the restriction that any edge (or sometimes vertex) cannot be simultaneously utilised by more than one item at once. Assuming that the problem does not also consider runway sequencing or stand allocation, the inputs to the problem usually consist of: a starting location and earliest starting time for each aircraft; a destination location for each aircraft; optionally, a latest time for each departure by which they must reach the runway (when there is a previously planned take-off sequence that must be achieved); and a directed graph of the airport taxiways, indicating how long each edge will take to traverse (explicitly, or by labelling it with enough information to apply a function to calculate it, for example when the time depends upon aircraft type). The outputs of the problem will be a routing for each aircraft, stating when it will be at each node/traverse each edge. Any sequencing of operations at intersections can be inferred very easily from these times.

A number of approaches have been applied to the ground movement problem in the past, including both heuristics (often Genetic Algorithm-based, e.g. [7]) and exact methods (often Mixed Integer Linear Programming-based, e.g. [11]), as discussed in [2]. The temporal aspect to the problem has been solved in the past in a number of ways. The simplest way is to consider the routing of aircraft in order, recording when edges and vertices become free again, so later aircraft have to use them after these times. This can be useful for real time routing, or when planning only a small amount of movement at a time per aircraft. A more flexible approach is to label edges or vertices with time windows when they are in use or not (so that aircraft considered later can still utilise earlier gaps which are large enough). The third approach used in the past involves discretising time, so that in each time instant only one aircraft can use the edge/vertex rather than considering how soon a resource will become free again.

The QPPTW (Quickest Path Problem with Time Windows) algorithm, studied in [6] and applied to airport ground movement in [3],[9], is a sequential algorithm which considers each aircraft one at a time and applies a process similar to Dijkstra's algorithm to route each aircraft, but considers each of the potential time windows which are available on each edge at the time, rather than the edge itself. As implied by the name, the temporal constraints are handled in this algorithm by labelling edges with time windows indicating when they are available for use. Initially, all edges are considered to be available all of the time, but as aircraft are routed, the times at which previous aircraft use the edges are removed from the available time windows for those edges, potentially splitting time windows and restricting the time available for future aircraft to be routed. The routing of later aircraft can, therefore, become increasingly complex and time-consuming at busy times.

In addition to its use for ground movement planning [3], the QPPTW algorithm has been used for a variety of research into the ground movement problem, including a consideration of fuel burn trade-offs [10] and an analysis of the effects of the delays that happen at pushback [14].

In most cases the QPPTW algorithm is already fast enough to solve real problems, however as the problem complexity increases, either in terms of the size and interconnectedness of the graph, or the number of aircraft which conflict with each other, its speed decreases. With the increasing pressure upon airports as the number of flights increase, maintaining this speed will become increasingly important for any practical decision support system which could utilise the algorithm. This research considers the QPPTW algorithm, and the potential for increasing the speed of this algorithm without decreasing the quality of results, through the use of appropriate pruning techniques to reduce the options which need to be considered for each aircraft.

Ravizza [9] (Section 6.4.5) previously investigated the use of estimated lower bounds (using both Euclidean Distance and Dijkstra's algorithm) for improving the search speed, but found no benefits, stating that this was potentially because the graph utilised was too sparse. However, in other situations, [13] and [12] (Chapter 6) identified significant speed benefits from utilising an A* algorithm with a shortest path calculated using Dijkstra's algorithm, reporting time reductions of 56% in [13].

This research considers the potential benefits of different approaches for estimating the remaining taxi time for aircraft, and their effectiveness for reducing the search time (without losing solution quality) in different situations, in terms of airport layout, starting and ending positions of journeys, and the amount of traffic on the airport surface at the time. This information has value in terms of determining when it is worth applying such pruning within the algorithm in specific applications; for example in determining whether a target airport has a layout for which the algorithm is likely to benefit from the addition of the pruning approach, or whether the pruning calculation times are likely to introduce an unnecessary overhead. These findings should also be of value for other situations, beyond the airport environment, where similar algorithms are employed.

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