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Optimal route decision with a geometric ground-airborne hybrid model under weather uncertainty

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ABSTRACT

Adverse weather is the dominant cause of delays in the National Airspace System (NAS). Since the future weather condition is only predictable with a certain degree of accuracy, managing traffic in the weather-affected airspace is a challenging task. In this paper, we propose a geometric model to generate an optimal combination of ground delay and route choice to hedge against weather risk. The geometric recourse model (GRM) is a strategic Probabilistic Air Traffic Management (PATM) model that generates optimal route choice, incorporating route hedging and en-route recourse to respond to weather change: *hedged routes* are routes other than the nominal or the detour one, and *recourse* occurs when the weather restricted airspace becomes flyable and aircraft are re-routed to fly direct to the destination. Among several variations of the GRM, we focus on the hybrid Dual Recourse Model (DRM), which allows ground delay as well as route hedging and recourses, when the weather clearance time follows a uniform distribution. The formulation of the hybrid DRM involves two decision variables – ground delay and route choice – and four parameters: storm location, storm size, maximum storm duration time, and ground-airborne cost ratio. The objective function has two components: expected total ground delay cost and expected total airborne cost. We propose a solution algorithm that guarantees to find the global optimum of the hybrid-DRM. Based on the numerical analysis, we find that ground-holding is effective only when combined with the nominal route. Otherwise, it is optimal to fly on the route determined by the DRM without ground delay. We also find the formula of the threshold ground-airborne cost ratio, which we call the Critical Cost Ratio (CCR), that determines the efficacy of ground delay: the higher the CCR, the more effective the strategies involving ground delay. We conclude that both ground delay and route hedging should be considered together to produce the best ATM decisions.

1. Introduction

There is a growing interest in Air Traffic Management (ATM) strategies that incorporate uncertainty in the national airspace system (NAS). Research in "probabilistic air traffic management" (PATM) seeks to guide decisions on ground-holding or otherwise modifying aircraft four-dimensional trajectories (4DTs) in order to minimize the expected cost, or to hedge against "worst case" scenarios in the Next Generation Air Transportation System (NextGen).

In this paper, we study the problem of developing a minimum-cost aircraft routing strategy when some weather condition inhibits the use of the nominal route for an indefinite period. In conventional Air Traffic Management (ATM), two

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options are commonly considered in such a situation; the flight is either held at the origin airports until the nominal route becomes flyable or rerouted to avoid the weather region entirely. The choice between these options is based upon a deterministic and conservative characterization of future weather, often resulting in underutilized airspace and unnecessary delay if the weather clears early.

We propose a geometric model to find an optimal combination of ground holding and route decision when the weather clearance time is stochastic. The route decision takes into account the probability distribution of storm clearance time, the possibility of route hedging, the cost difference between ground delay and airborne, and the recourse opportunities. When facing uncertain weather, there are two potential risks to hedge against: persistence risk and clearance risk. Persistence risk is the risk when we take an ‘‘optimistic’’ route and weather persists, resulting in unplanned re-routing and delay. Clearance risk is the risk when we take a ‘‘pessimistic’’ route and weather clears sooner, resulting in unnecessary extra flight time. To mitigate these risks, we consider the intermediate routing options that may not be optimal under either persistence or clearance, but hedge against either possibility. In doing so, we consider how the route might be adjusted if the weather clears during the course of the flight. We assume that the flight plan can be amended in such an event so that the plane can fly direct to the destination.

We first discuss optimal routing decision based on the geometric optimization model without considering ground holding. In this model, the routing decision is made based on four parameters; nominal route between origin and destination airport, storm location, storm size, and maximum storm duration time. The optimistic route is the nominal one while the pessimistic route goes around the storm. A hedged route is one that is between the optimistic and the pessimistic one. We use the term *recourse* for a change in a routing that results from the storm clearing. We consider two recourse possibilities. First, the storm may clear before the aircraft reaches it, so that it can be rerouted directly to its destination. This is called *first recourse*. The storm may instead persist beyond the time when the aircraft reaches it—so that the plane must turn and begin to fly around it– but clear before the tip of the storm is reached. The aircraft may then be rerouted direct to the destination; we refer to this as *second recourse*.

In our model, which we term the Geometric Recourse Model (GRM), a triangle is drawn in which the base is the nominal route between the origin and destination, and the vertex is the tip of the storm, which we assume to be a straight line perpendicular to the nominal route. We seek routes that minimize expected total flight cost, which in some cases are hedged routes. Out of several variations of the geometric recourse model, we consider the Dual Recourse Model (DRM). The DRM allows both the first and second recourses to assume greater responsiveness to changing conditions and consequently results in reduced cost. We discuss a set of conditions that guarantees the nominal route to be optimal in the DRM, regardless of the probabilistic nature of the weather clearance time.

Following discussions on the formulation and properties of the DRM, we extend the model with the ground delay option at the origin. The ground-airborne hybrid model, or the hybrid-DRM, finds the optimal combination of ground holding and airborne routing based on the weather characteristics as well as the cost difference between ground holding and additional airborne time. We propose a solution algorithm to find the optimal solution of the hybrid-DRM. In searching for a solution, the algorithm finds the range of the ground-airborne cost ratio for each optimal ground holding and route combination. In model analysis, we find that it is optimal to take positive ground delay only when the ground-airborne cost ratio is below a certain threshold value, which we call the Critical Cost Ratio (CCR), and no ground holding is necessary otherwise. The Critical Cost Ratio (CCR) is found as a formula in weather parameters. We also find that the positive ground holding is optimal only when combined with the nominal route. When ground holding is inappropriate, the hybrid-DRM reduces to the DRM, which determines the optimal route choice.

In our models, the probabilistic nature of the weather is represented with its clearance time. Although it is more realistic to assume that the weather condition either improves or deteriorates gradually rather than changes instantaneously, the weather clearance time is an effective and practical representation of the time when the airspace becomes flyable. A similar idea applies to the storm represented as a perpendicular line to the nominal course. The line should be understood as a control point to let the traffic go through or not, behind which convective weather exists.

2. Literature review

There have been numerous efforts to address weather-related disruptions in air traffic management. Earlier traffic flow management models such as Bertsimas and Patterson (1998) and Goodhart (1999), often have a deterministic setting. More recently, Nilim et al. (2001), Nilim and Ghaoui (2002, 2004) proposed a dynamic aircraft routing model with robust control. Their research adopted shortest-path algorithms in a grid structure, by discretizing time into stages when the routing decisions are made, and airspace as a two-dimensional grid. The weather condition in each potential storm region is assumed and modeled as a Markovian process with two states: 0 (No storm) and 1 (Storm). The transition matrix is estimated based on the historical weather forecasts. Optimization results show a promising improvement compared to simply flying around the storm.

In the air transportation system, however, the frequent routing adjustments entailed by such an approach may place undue workload on controllers and pilots. Moreover, the Markovian assumption is of doubtful validity in the context of convective weather. Two of the goals in our study are to set up a model that has the flexibility to adopt a variety of probability distributions of storm clearance times, and to limit re-routing decisions to a reasonable number.