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# Ground delay program planning: Delay, equity, and computational complexity

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ABSTRACT

The Federal Aviation Administration, in consultation with air carriers, manages Ground Delay Programs, delaying aircraft scheduled to land at capacity constrained airports prior to takeoff to increase the safety and efficiency of air travel. Prior research optimizes Ground Delay Program planning to minimize either delay or a weighted combination of delay and measures of inequity, a key concern in practice. Such approaches have several shortcomings including an inability to find all Pareto-optimal policies and a reliance on (one or many) models relating fundamentally incompatible objectives. This article introduces several two-phase approaches to Ground Delay Program planning that address the problems of weighted sum methods while managing computational burdens, another key concern in practice. A computational study demonstrates the benefits of the new approaches on realistic problem instances.



## 1. Introduction

The number of aircraft scheduled to land at or takeoff from certain airports, or fly through certain sections of airspace, sometimes exceeds the capacity of the current air transportation system. Visibility, wind, and weather conditions determine how many aircraft can be safely and efficiently accommodated at airports but these conditions change relatively rapidly. In the United States, the Federal Aviation Administration (FAA) institutes Air Traffic Flow Management (ATFM) programs including Ground Delay Programs (GDPs) and Airspace-Flow Programs (AFPs). GDPs and AFPs delay the departure times of aircraft that are scheduled to utilize capacity constrained destination airports and sections of airspace, respectively. The goal is to replace airborne delay with ground delay, to reduce airline fuel costs and air traffic controller workloads while increasing passenger comfort and safety. Prior studies note that the GDP is the "most comprehensive" tool at the disposal of the FAA (Glover and Ball, 2012). 1305 GDPs were implemented in the United States in 2006 (Kotnyek and Richetta, 2006).

GDPs and AFPs are currently managed according to heuristic procedures, but a number of articles propose the use of computerized systems to optimize decision-making. One paper notes "computer-based decision support systems might improve ATFM performance significantly" (Lulli and Odoni, 2007). The majority of studies minimize the costs of delay incurred by aircraft (e.g., Bertsimas and Patterson, 1998). The use of stochastic optimization allows researchers to account for uncertainty inherent in ATFM decision-making. The computational burdens of solving identified (large-scale, stochastic, mixed integer linear programming) problems presents an interesting challenge. A number of studies include formulations of ATFM problems meant to ease computational burdens or investigations into the computational performance of alternate formulations of ATFM problems (e.g., Bertsimas and Patterson, 1998; Hoffman and Ball, 2000).

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FAA operations today are based on the paradigm of Collaborative Decision Making (CDM), where air carriers are consulted and given substantial authority. CDM is in use in part to ensure equitable treatment of air carriers (Glover and Ball, 2012). The "fundamental principle" of GDP decision-making today is Ration by Schedule (RBS), which requires that aircraft be assigned access to a capacity constrained airport according to a schedule that preserves the order of the pre-GDP schedule (Gupta and Bertsimas, 2010). A similar principle holds in Europe (Castelli et al., 2011). The RBS rule has the potential to increase the system-wide costs of delay. For example, as adverse weather clears and airport arrival capacity increases, aircraft that are being held at relatively close origin airports may be delayed waiting for aircraft that are further away but scheduled to land earlier. The FAA recognizes this problem and will exempt "long-haul" flights from GDPs (Glover and Ball, 2012), a heuristic approach to mitigate the efficiency costs of RBS. As numerous researchers have noted previously (e.g., Lulli and Odoni, 2007), the objectives of equity and efficiency are conflicting.

One article notes "since there will typically be a trade-off between aggregate system delay and any flight-based fairness criterion, [a new] formulation should essentially consider a bi-criterion approach" (Fearing et al., 2009). Addressing this claim, researchers combine equity and efficiency criteria, using what is known as *the weighted sum approach*. Separate objective functions are crafted to capture equity concerns and delay costs, then these objective functions are weighted and summed to yield a composite objective function for decision making (e.g., Mukherjee and Hansen, 2007; Fearing et al., 2009; Gupta and Bertsimas, 2010; Glover and Ball, 2012). The weights given to the different objective functions are often varied, as sensitivity analysis. One group of authors write "we applied non-negative weights that summed to one on each of the objective function components and varied each weight from 0 to 1, incrementing by 0.01" (Glover and Ball, 2012).

There are several shortcomings of the weighted sum approach. The primary definition of optimality in a multi-objective setting is Pareto-optimality. A policy is Pareto-optimal if it is impossible to improve one objective without scoring worse in terms of another. The weighted sum approach is incapable of finding all Pareto-optimal policies. In the worst-case, the approach reveals delay minimizing and equity maximizing ATFM policies but not any of arbitrarily many Pareto-optimal policies between these two extremes. Selection of the "optimal" ATFM policy is sensitive to weights used even though little confidence can be placed in any set of weights (Ehrgott, 2005). Sensitivity analysis is an imperfect solution. The analysis described above required solving 101 variants of a problem known to be computationally challenging, regardless of how many, if any, new solutions could be uncovered. Finally, efficiency and equity are incompatible objectives; a composite objective function lacks intuitive meaning. Operations researchers select and parameterize a model combining the two objectives when using a weighted sum approach. Arguably such analysis is best left to FAA and airline decision makers.

A brief illustration of the failure of the weighted sum approach to find certain types of Pareto-optimal policies is presented here. Two objectives of GDP planning include minimizing the total expected delay and minimizing the deviation from the (equitable) RBS schedule (Glover and Ball, 2012). It is common to compare alternate decisions or policies by plotting the *objective space*. Fig. 1 contains three plots depicting the same sample objective space and solutions to a bi-objective GDP planning problem. The outcomes highlighted by red arrows in the plot at left are Pareto-optimal, clearly the best options. Minimizing a weighted combination of the objectives is intuitively equivalent to pushing a diagonal line with a negative slope, starting at the upper right hand corner of the plots of Fig. 1, and pushing the line down and to the left through the objective space. The last point hit represents the optimal policy. The plot in the middle of Fig. 1 illustrates the process. If substantially more weight is given to equity relative to efficiency, than a small change in equity is as important as a large change in efficiency. Push a relatively horizontal line down and to the left through the objective space; point f is preferred. Valuing efficiency much more than equity is equivalent to pushing a relatively vertical line through the space and point a is optimal. For some intermediate sets of weights, point c is selected, as shown in Fig. 1. Points b, d, and e will never be found in this manner. As the plots in the middle and at right make clear, these points are in the interior of the space of solutions. Any line going through these points can be pushed further down and to the left and hit another plotted point; any weighted sum

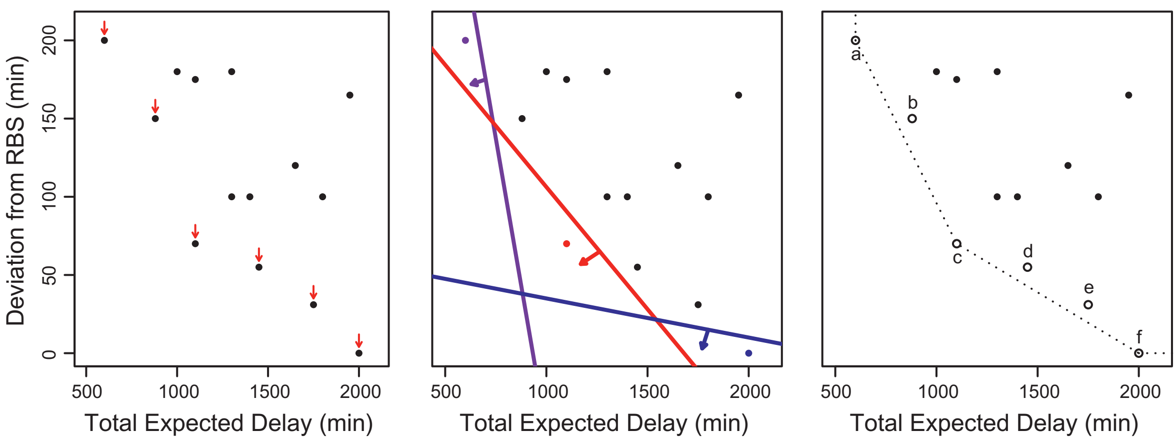


**Fig. 1.** Sample solutions for a bi-objective GDP planning problem.