Chapter 1

Introduction

Air travel, for both business and pleasure, has become a part of daily life in the developed nations of the world. The Federal Aviation Administration (FAA) reported that, during 1997, air traffic controllers handled more than 25 million flights in the United States alone [48]. Continued economic growth portends a steady increase in air traffic for the foreseeable future. As a result, we can anticipate a more congested and potentially problematic airspace, particularly in and around major transportation hubs.

Certainly, airspace is a finite resource. Higher traffic densities cause more flights to be rescheduled or rerouted to avoid conflicts, more delays for aircraft arriving and departing from terminals, and increased instances of near misses between aircraft. Several research analyses, including one recently conducted by the Office of Technology Assessment, have demonstrated that linear increases in air traffic operations result in a quadratic increase in collision risk [37].

Severe weather systems induce the dynamic closures of large regions of airspace to avoid such dangerous meteorological conditions. En route aircraft must be redirected around these airspace regions. When severe weather disrupts airport operations, in-bound flights must be held at their origin airports or be rerouted to another airport. Outbound flights must be grounded until the severe weather passes or dissipates. The resulting flight delays and cancellations cascade through the National Airspace (NAS), particularly when such conditions strike high traffic airports such as Chicago’s O’Hare International Airport or New York’s John F. Kennedy Airport.

The burgeoning space transportation industry is expected to begin having a significant impact on the NAS within the next 10 years. Space launch requires the cordoning of large areas of controlled airspace to allow for launch and reentry of spacecraft. Currently, space launch operations are limited primarily to Cape Canaveral Air Force Base and Kennedy Space Center, Florida, and Vandenberg Air Force Base, California. However, there are proposals for at least twelve more spaceports. It is imperative that we begin to integrate air and space resource requirements in the near-term to coordinate the increasing demand for airspace by commercial air-traffic and space launch and recovery operations.

The airline industry is a highly competitive business having a significant impact on the overall U.S. economy. This was never more evident than during the extraordinary aftermath of the terrorist attacks of September 11, 2001. The airline industry suffered catastrophic revenue losses, subsequently requiring the federal government to provide $15B in emergency economic relief. The size and scope of the financial bailout was unprecedented, but it was necessary to avoid corporate failures that would have severely undermined the national economy and its infrastructure.

Clearly then, it is in the nation's interest to ensure safe and dependable use of the NAS, even as increased demand strains air-traffic management capabilities. Furthermore, it is essential that we take steps to encourage new entrant airlines and develop new services for smaller communities to ensure a healthy and competitive industry in the long term. Accordingly, the Federal Aviation Administration (FAA) is sponsoring an overall 10-year, $11.5B, effort to increase NAS capacity by 30 percent [13]. The model developed herein contributes toward these goals.

1.1. Scope of Research

In this dissertation, we develop an Airspace Planning and Collaborative Decision Making (APCDM) model that can function as both a tactical and a strategic tool enabling more efficient use of constrained NAS resources, and reducing costs associated with flight delays and diversions. Given a set of flights that must be scheduled during some planning horizon, we use a mixed-integer programming formulation to select flight plans from a set of alternatives, called *surrogates*, subject to certain flight safety, air traffic control workload, and airline equity considerations. The model is tested using the FAA's NAS traffic demand scenario flight data, namely, the Enhanced Traffic Management System (ETMS) database. Each fight plan is given by a set of four-dimensional coordinates (latitude, longitude, flight level, and time). Accordingly, a complete aircraft trajectory is taken as a series of piecewise linear trajectories, calculated as convex combinations of adjacent *waypoints* in three-dimensional space, as a function of time.

The APCDM uses two sub-models to pre-process data, the Airspace Occupancy Model (AOM) [48] and the Probabilistic Aircraft Encounter Model (PAEM). The AOM model encapsulates a mathematical representation of the NAS. Each flight plan is analyzed to determine the sectors it traverses along with the time intervals associated with each sector crossing. By examining maximal overlapping sets of sector occupancies, we can determine each sector's maximum air traffic control monitoring workload as a function of flight plan selection. A maximal workload restriction for each sector is appropriately included in the proposed model.

The Probabilistic Aircraft Encounter Model (PAEM) examines *conflict risk* issues in the enroute airspace. As an enhancement to previous research, we consider random errors for each aircraft about the planned or filed trajectory rather than assume deterministic flight paths, recognizing that aircraft are subject to pilot, navigation, and wind-induced errors. We perform a pairwise aircraft trajectory analysis, defining conflict risks in terms of threshold parameters corresponding to the probabilistic intrusions of different *intruder* aircraft into the rectangular-shaped restricted airspace region, called a *proximity shell*, surrounding each given *focal* aircraft.

We develop two alternative representations of maximal trajectory displacement errors and use them to describe the probabilistic positions realized at each waypoint. The first is a rectangular region that models random trajectory deviations. The second is a partial cylindrical conic region that models wind-induced errors. We partition these maximal displacement regions into sub-regions and use the geometric centroid of each sub-region as the trajectory error realization, with the probability of this realization being the integral of the three-dimensional probability density function over the corresponding sub-region.

A conflict analysis is conducted for every combination of trajectory realizations for each aircraft pair. The conflict probabilities and time intervals corresponding to each pair of realizations are then aggregated to produce an overall conflict risk time interval.

The conflict intervals produced by the PAEM model are then used to generate a set of conflict resolution constraints. These constraints limit the number of simultaneously occurring conflicts so that the induced workload is within each sector's respective capacity for safely monitoring and resolving such conflicts. In contrast with a previous approach that used discretized time-slots, we employ a continuous time formulation that eliminates the need to discretize the time horizon by incorporating a practical conflict resolution *prep-buffer* for each conflict interval. We prove that the continuous time formulation provides a spectrum of representations, ranging from less restrictive to more restrictive relative to the discrete time formulation, depending on the prep-buffer durations. This formulation provides added flexibility in representing the conflict resolution capacity of the various air traffic control sectors in practice. Note that in addition to the aforementioned explicit (hard and soft) maximal workload constraints, these conflict resolution constraints provide additional implicit sector workload restrictions.

A conflict graph is constructed to represent the probabilistic conflicts between aircraft pairs, and then examine various special sub-graph structures to develop provably stronger linear programming relaxations. More specifically, we introduce a set of valid inequalities corresponding to node triplets that do not admit a clique in any of the considered conflict graphs. We prove that the resulting constraint formulation is tighter in its linear relaxation than that used in the preliminary APM model [47]. We then propose some additional valid inequalities that may be used to tighten this representation. We also propose a further enhanced formulation based on incorporating certain higher-dimensional underlying star graph convex hull constructions, and demonstrate that this provides an even tighter representation.

The Airspace Occupancy Model (AOM) identifies the sectors traversed by each surrogate flight plan, along with the respective sector occupancy time intervals. From this information, we can determine the maximum air traffic density in each sector of interest that will result from the selection of any set of flight plans. Using a suitable workload function, we assign a cost corresponding to the air traffic control workload required to safely monitor and direct the composed mix of flight plans. By combining this with the conflict resolution constraints derived via the PAEM model, we obtain a comprehensive representation of air traffic control workload issues for the various sectors.

A novel contribution of this research that is of great contemporary interest to the FAA and the airline industry in the context of the Collaborative Decision Making (CDM) environment is the consideration of equity among airline carriers in absorbing the costs related to re-routing, delays, and cancellations. We first propose an improved set of cost factors. In addition to fuel and delay costs considered in [47], we examine flights that are linked as a result of hubbed operations. We identify flight plans that are a part (called a *leg*) of a series of flights that are dependent upon each other. We use this hierarchy of dependencies to assign additional costs when an upstream flight leg delay impacts downstream flight legs. Recognizing that consumers choose flights based on factors such as schedule convenience, reliability, and timely connections, we include a consideration of market costs in the cost model.

Next, we introduce a concept of *collaboration efficiency* as the cost difference between each flight's individually optimized flight plan and the flight plan selected by the model. The APCDM constraints preclude the selection of flight plans that cause an airline to incur such costs beyond a specified maximal limit. This concept is used to develop an equity formulation that assesses the distribution of collaborative efficiencies achieved by each airline, and we exhibit that this approach is superior to previous modeling efforts that employ a minimax strategy with respect to the spread of these efficiencies. Accordingly, a *collaboration equity* function is defined as the summation of the absolute differences between each airline's collaboration efficiency and an overall industry-wide weighted average collaboration efficiency. This function, along with the other accompanying measures, are included in the APCDM objective function via appropriate, commensurate penalty terms.

An alternative equity representation is presented that maps collaboration efficiencies and equities to respective exponential utility functions. This equity formulation allows us to consider the significance of risk attitudes revealed by airline decision makers with respect to costs, and to examine scenarios where these decision makers might “game” their decisions in the collaborative process. We then investigate various piecewise linear representations of such utility functions, and compare this formulation with the foregoing linear alternative to determine the relative merits of these alternative modeling strategies.

The model is tested to consider various airspace restriction scenarios imposed by dynamic severe weather systems and space launch Special Use Airspace (SUA) impositions. Using the APCDM output from such scenarios, we present some further analysis to demonstrate how these solutions could be fed back into our overall model to generate new flight plans that are superior (in terms of achieving lower collaboration costs) to the existing surrogates. This type of an analysis can serve a useful role in augmenting the FAA’s *National Playbook* of standardized flight profiles in different disruption-prone regions of the National Airspace.

1.2. Summary of Contributions

This dissertation makes the following specific contributions in developing an enhanced airspace collaborative decision making model.

1. We incorporate two alternative representations of randomized aircraft trajectory errors into the model versus using deterministic flight paths, recognizing that aircraft are subject to pilot, navigation, and wind-induced errors. By studying various conflict risk thresholds, we offer new insights that can be used for investigating possible revisions to FAA’s aircraft separation standards.

2. Our continuous time formulation of conflict risk intervals provides a more flexible means to study sector conflict resolution capacities.

3. We propose two model representations having tighter linear programming relaxations that significantly increase the solvability of the developed large-scale mixed-integer optimization problem.

4. A flight plan cost model is proposed that includes a more comprehensive consideration of diverse aircraft characteristics and routing requirements. We use this cost model to implement a novel collaboration equity formulation. This formulation scrutinizes the distribution of individual airline schedule costs relative to the overall cost.

Previous modeling efforts were limited to minimizing the maximum deviation of individualized costs from the average cost.

5. The model can be used in practice for various tactical decisions as well as strategic planning scenarios. Potential tactical decision making contexts include air traffic control diversions and delays during spacecraft launch operations or during severe weather conditions, military theater operations (such as damage assessment, search and rescue, ground support, and counter-operations), and the generation of alternative flight plans. Strategic applications include air traffic control policy evaluations, homeland defense contingency planning, spaceport location planning, and military theater air campaign planning. Furthermore, the model can be used to study the incorporation of the Small Aircraft Transportation System into the NAS, and evaluate possible revisions to aircraft separation standards.

1.3. Organization of the Dissertation

The remainder of this dissertation is organized as follows. In Chapter 2 we review the relevant literature, beginning with air traffic management issues arising from increased demand and the resulting traffic density. We discuss several air traffic management techniques currently in use and the tools employed to identify and redirect conflicting aircraft. Chapter 2 concludes with a brief overview of the preliminary Airspace Planning Model [47] and its two sub-models, the AOM and the AEM [48].

We present the PAEM in Chapter 3. We begin by describing the geometric transformations necessary to perform the conflict analysis from the perspective of each focal aircraft's trajectory. Next, we propose some probabilistic trajectory error models, and introduce two alternative representations for the maximal trajectory displacement regions. Our discussion of the PAEM concludes with some comments regarding its implementation.

Based on the foregoing analysis, we address the formulation of various conflict resolution and associated workload constraints in Chapter 4. First, we present a continuous time formulation that utilizes conflict prep-buffers. After reviewing the conflict resolution constraints previously incorporated within the APM model, we develop enhanced formulations for these restrictions, and prove that they progressively provide tighter linear programming relaxations. We also include a discussion of the algorithms necessary to generate these constraints.

The model's equity representation is developed in Chapter 5. We define a detailed flight plan cost model, and then describe the concepts of collaboration efficiency and collaboration equity. These are subsequently incorporated into the model via suitable utility functions and penalty terms.

In Chapter 6, we present the overall mixed-integer APCDM model, and summarize its components that were developed in the previous three chapters. We perform a structural analysis of the model and comment on its overall implementation via the CPLEX-MIP software.

We present our computational results in Chapter 7. We describe the several ETMS database scenarios used and report the results obtained from the APCDM output. We experiment with conflict analysis parameters to determine their impact on flight plan selection, and ascertain the respective effectiveness of the two conflict resolution constraint formulations. Likewise, we investigate the alternative proposed representations of equity considerations. We also report the model's response to weather and SUA restrictions, and identify possible flight plan adjustments that could be employed to minimize the impact of these restrictions on NAS operations.

Finally, in Chapter 8, we discuss the overall effectiveness of the proposed APCDM model and summarize its contributions toward the effort to improve NAS operations. We conclude the dissertation by recommending several avenues for future research in this rich area of great contemporary public interest and national importance.