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A Scenario-Based Approach for the Air Traffic Flow Management Problem with Stochastic Capacities

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Abstract**—**In this paper, we investigate the strategic stochastic air traffic flow management problem which seeks to balance airspace capacity and demand under weather disruptions. The goal is to reduce the need for myopic tactical decisions that do not account for probabilistic knowledge about the NAS near-future states. We present and discuss a scenario-based modeling approach based on a time-space stochastic process to depict weather disruption occurrences in the NAS. A solution framework is also proposed along with a distributed implementation aimed at overcoming scalability problems. Issues related to this implementation are also discussed.

Keywords**—**Air traffic management, sample average approximation, scenario-based approach, stochastic capacity.

I. Introduction

IN the last few years, the National Airspace System (NAS) capacity has been seriously challenged. The increase in flight delays and their cost to national economy is a clear evidence of this problem. According to the Congress Joint Economic Committee (JEC) [1], the total cost of flight delays in the US was estimated to $41 billion in 2007. Additionally, the Federal Aviation Administration (FAA) anticipates air traffic operations to increase as much as 250 percent by 2025 [2]. Fig. 1 shows the large and complex activities in the NAS. Clearly, if no actions are taken, the NAS will be unable to handle this significant demand surge and flight delays are likely to be more pronounced. Fig. 2 shows causes of flight delays in the NAS during 2012. As indicated in this figure, weather accounted for approximately 70% of these delays. Hence, accounting for weather disruptions in managing airspace capacity is a key factor to overcome current and future airspace growth challenges. In fact, increasing capacity through infrastructure investments is costly and may be unfeasible in some cases. Moreover, solely adding more infrastructures is unlikely to solve the problem. The alternative is a better airspace management through the elaboration of approaches that balance demand and capacity under uncertainty especially when induced by convective weather. The effective allocation of demand under uncertainty is in fact one of the Next Generation Air Transportation System (NextGen) primary objectives. NextGen will indeed allow advanced technological tools and a better weather forecast. However, the inherent stochasticity of weather requires the development of stochastic approaches for airspace management. To this end, both effective tactical operations (i.e., real-time) and strategic planning (i.e., a few hours) are needed.

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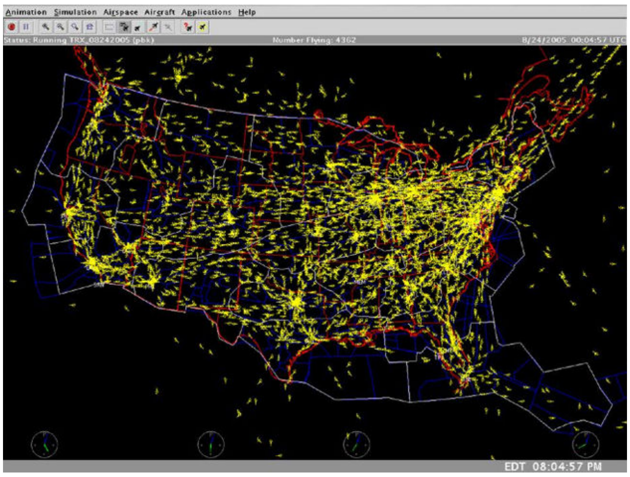

Fig. 1 The Large and Complex NAS (source: NASA Web Site)

Causes of National Aviation System Delays
National (January - December, 2012)

	Number of Operations	% of Total Operations	Delayed Minutes	% of Total Delayed Minutes
Weather	176,102	58.69%	8,952,227	69.81%
Volume	84,912	28.30%	2,465,717	19.23%
Equipment	1,230	0.41%	57,894	0.45%
Closed Runway	24,808	8.27%	930,984	7.26%
Other	13,010	4.34%	416,393	3.25%
Total Operations	300,062	100.00%	12,823,215	100.00%

A flight is considered delayed when it arrived 15 or more minutes than the schedule (see definitions in Frequently Asked Questions). Delayed minutes are calculated for delayed flights only. This section reports delayed minutes.

SOURCE: Federal Aviation Administration OPSNET

Fig. 2 Causes of NAS Delays in 2012

In this work, we investigate the strategic stochastic air traffic flow management problem which seeks to balance airspace capacity and demand under weather disruptions. The goal is to reduce the need for myopic tactical decisions that do not account for probabilistic knowledge about the NAS near-future states. We propose a scenario-based modeling approach based on a time-space stochastic process to depict weather disruption occurrences in the NAS. The proposed approach allows characterizing the impacts of convective weather on airspace capacity over the planning time horizon. A solution framework is then proposed to allocate demand using stochastic time-dependent airspace capacity.

II. The Stochastic Air Traffic Flow Management Problem

The Stochastic Air Traffic Flow Management problem (SATFM) is aimed at balancing airspace demand with stochastic airport and en route capacities using recourse actions that include ground and airborne holding, rerouting and speed control. Compared to the SATFM, the literature of its deterministic counterpart (ATFM) which assumes deterministic capacities has been more extensive. Interesting survey papers on ATFM can be found in [3]-[5]. ATFM seeks to determine each flight sequence from its origin to its destination using capacitated airspace sectors. Decisions about rerouting as well as the amount of holding time on the ground and in the air must also be made for each flight in order to minimize the total delay.

In the past few years, there has been an increased interest in SATFM. In [6], Nilim and El Ghaoui modeled weather evolution as a stationary Markov chain and proposed a stochastic dynamic programming algorithm. Chance Constrained Programming was used in [7] where the authors modified a deterministic Mixed-Integer Linear Programming to include constraints on the likelihood of sector capacity violations given probabilistic information about the future capacity states. Some authors proposed scenario based models and used different approaches to overcome scalability issues. Hence, scenario tree based schemes were used in [8]-[11] while a Danzig-Wolfe decomposition was proposed in [12]. In [13], the author presents a rolling horizon method that solves the problem by dividing it into several smaller problems solved in sequence.

Despite this growing interest in the field, existing papers often simplify the problem to reduce its complexity (e.g., a single sector, airport capacity only, validation on small sized problems that do not represent real-life problems as encountered in the NAS, etc…).

III. Scenario-Based Approach

The first step in developing a scenario-based modeling approach is to characterize weather impacts on airspace capacity. Some papers in the literature attempt to link weather disruptions to airspace capacity fluctuations [14]-[16]. Recently some authors proposed simulation-based approaches that use ensemble-based weather forecasting to predict weather effects on airspace capacity [17], [18]. However, there is still a lack of models that adequately account for the complexity of weather patterns to properly depict their impacts on the airspace capacity. Particularly, very few papers in the literature account for the temporal and spatial evolution of weather patterns [19], [20].

A. Modeling Framework

Inspired by our previous work on modeling hazard impacts on relief distribution networks [21], [22], we propose a time-space stochastic process to depict weather disruption occurrences in the NAS which is partitioned into sectors. Accordingly, during the planning time horizon, each weather disruption is characterized by the following attributes: occurrence time, centroid, duration, trajectory and intensity. The impact on the airspace is captured as follows. At each time within weather disruption duration, impacted neighboring sectors are identified using propagation probabilities and taking into account the storm trajectory. Then, at each time t within storm duration, capacity reduction at each affected sector s is computed taking into account the storm intensity level at sector s during time t. A set of probabilistic scenarios is then generated using the resulting stochastic process. Each scenario represents realizations of stochastic time-dependent capacities at the airspace sectors.

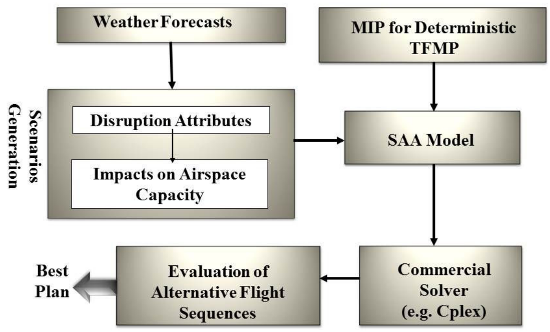

Fig. 3 Overview of the proposed solution framework

B. Solution Framework

The problem with stochastic time-dependent capacities can then be formulated as a linear stochastic optimization model using sample average approximation (SAA) method and a deterministic MIP model that includes ground and airborne holding, rerouting and speed control such as the one proposed in [23]. A commercial solver such as CPLEX is then employed to solve the SAA model and obtain several alternative solutions to choose from (i.e., alternatives for flight sequences). Finally, an evaluation of these alternatives is conducted (either by the user or automatically) to identify the best plan. Fig. 3 summarizes the proposed solution framework.

Time efficiency of the SAA method depends on the number of scenarios used in the model and in the evaluation of flight plans. To overcome this problem, we propose to use a parallel implementation. The parallelization of the approach can be done at two levels:

1. Different MIP solution search threads run in parallel, each of them solving the ATFM for a given scenario.
2. Within each search thread, decompose the problem into individual flight sub-problems where each flight

optimizes its own plan while taking into account system capacity. The challenge is to find an accurate decomposition mechanism that will effectively allocate restricted sector capacities to multiple users. A master–slave scheme can be used to implement the procedure. The master process is responsible for managing airspace sector capacities and equitably allocating these limited resources to requesting flights.

IV. Conclusion

In this paper, we addressed the air traffic flow management problem with stochastic time-dependent sector capacities. We presented a scenario-based modeling framework to formulate the problem and proposed a solution framework based on sample average approximation method. The resulting sample average approximation program typically leads to a large-scale mixed integer program solvable for problems of limited sizes and for a limited number of scenarios only. To cope with this problem, a distributed implementation of the approach was proposed and discussed. On the other hand, a key element to the success of this approach is the accuracy of the scenarios used. Our current work is aimed at generating scenarios that are inspired by real-life situations. We are currently in the process of collecting real-world data that represent The NAS conditions. Subsequently, OPL-Cplex optimization software will be used to solve the problem to optimality for scenarios with small sized problems. Future work will be aimed at exploring parallel implementations and decomposition procedures to further improve the proposed approach time efficiency.

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