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A sequence model for air traffic flow management rerouting problem

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ABSTRACT

With the continuous growth of air transportation industry, the current Air Traffic Management systems can hardly meet the demand recently. In this work, an integer optimization model for Air Traffic Flow Management (ATFM) which integrates 4D trajectory-based operations is proposed to improve the situation. Besides addressing the issues of rerouting, ground-holding delay, fuel consumption and flight cancellation on a flight-by-flight basis, the model also employs sector-less airspace configurations. In order to solve the model efficiently, Dantzig-Wolfe decomposition and a heuristic approach via column generation are developed to generate 4D conflict-free trajectories for each flight. By applying commercial optimization software, solutions could be obtained in 20 min for the ATFM rerouting problems of the whole Southeast Asia region.

1. Introduction

With the recovering global economies, air travel demand has been increasing rapidly. The Federal Aviation Administration (2013) (FAA) predicted that the U.S. carrier passenger growth rate is approximated to be 2.2% annually in the next 20 years, and the passenger demand over Asia-Pacific area is estimated to increase 4.3% per year. This continuous growth of air transportation industry has put tremendous pressure on the aviation system. Airspace congestion frequently happens because adverse weather always makes airspace unflyable. The U.S. Dept. of Transportation reported that approximately 21.6% of the flights within the United States were delayed in 2014 and 2.25% were canceled (Bureau of Transportation Statistics, 2014). The cancellation ratio has hit record highs during 2014 (Fig. 1). In 2004, the European Commission launched the Single European Sky ATM Research (SESAR) program to restructure the European airspace, create additional capacity and increase the overall efficiency of the ATM system. Whereas in 2007, the Joint Planning and Development Office of the U.S. initiated a long-term program which is called the Next Generation Air Transportation System (NextGen). The Motivation of NextGen is to improve ATM systems in various aspects such as terminal operations, coordination between all ATM subsystems, tracking on the airway and aircraft monitoring technology. SESAR and NextGen have different implementation frameworks, but they are all developing state-of-the-art technologies to enable aircraft fly their preferred 4D trajectories without limitations.

The motivation of this paper is to propose a type of trajectory-based Air Traffic Flow Management (ATFM) system to support SESAR and NextGen. In this work, we embed 4D trajectory-based operations into ATFM to minimize total delay cost and improve the capacity of airspace, while achieving energy-efficiency. ATFM is a strategic planning methodology introduced by Odoni (1987) which is employed to smooth the air traffic flow at an optimal rate while not exceeding the capacities of airports and other facilities. Nowadays, ATFM plays a crucial role in minimizing air traffic delays with the continuous growth of air transportation industry. In the framework of ATFM, there are two stakeholders: Air Navigation Service Providers and Airlines. Air navigation

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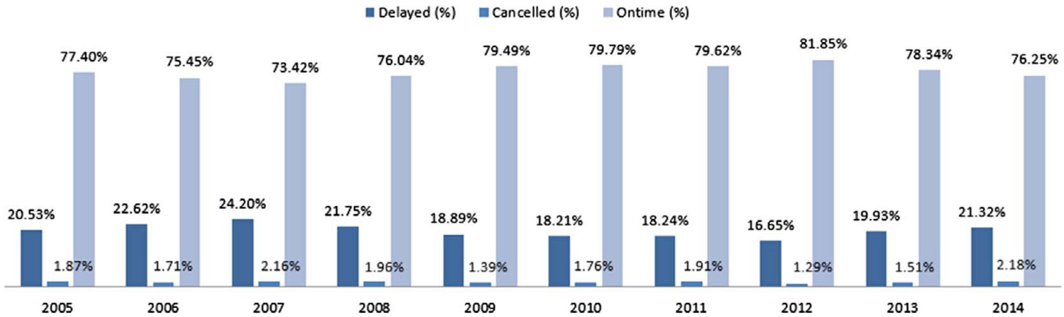

Fig. 1. On-time performance. (Data Source: Bureau of Transportation Statistics, 2014.)

service providers take charge of the functioning of the whole ATFM system. In the U.S., the principal air navigation service provider is the FAA, and in Europe, EUROCONTROL provides service to all users. Airlines are the primary users of the navigation service. Navigation service providers have several types of practical ATFM tools which are depicted in Fig. 2 to control all phases of each aircraft from taking-off to landing, and these approaches include Ground Delay Program (GDP), Airborne Holding Delay, Rerouting and Speed Control.

The initial ATFM models are proposed to solve the Ground-Holding Problem (GHP) which concentrates on how to assign ground-holding delays. Terrab and Odoni (1993) and Richetta and Odoni (1993, 1994) develop different approaches to address the problem of assigning ground-holding delays for a single destination airport (Single-Airport Ground-Holding Problem). Multiple-Airport Ground-Holding Problem (MAGHP) is studied by Vranas et al. (1994). In recent years, ATFM models start to address the sector capacity constraints. Agustin et al. (2010) classify these problems as Air Traffic Flow Management Problem (ATFMP) and Air Traffic Flow Management Rerouting Problem (ATFMRP). The only difference between the two problems is that rerouting operations are allowed in ATFMRP. Bertsimas and Patterson (1998) prove ATFMP is NP-hard and propose an integer programming model for the deterministic multi-airport ATFM problem. The ATFM situations of the U.S. and Europe are different: in the U.S., the restriction of ATFM system is the Airport Acceptance Rate, whereas, in Europe, sector capacity acts as the bottleneck. Lulli and Odoni (2007) provide an integer optimization approach to address the peculiarities of European ATFM problems, and they obtain a counter-intuitive conclusion that airborne holding delay sometimes can reduce the total delay cost in Europe. Bertsimas and Patterson (2000) solve the multi-airport ATFMRP by applying a dynamic network flow approach. Bertsimas et al. (2011) propose an ATFMRP model on a flight-by-flight basis and employ strong valid inequalities to solve large-scale applications efficiently. Churchill et al. (2009) point out that ATFMRP is hard to solve because too many sectors must be included, and they introduce a revised airspace structure based on Bertsimas et al. (2011)'s work to improve computational performance. Mukherjee and Hansen (2009) present a model for ATFMRP to reroute flights inbound to airports dynamically. Dell'Olmo and Lulli (2003) develop a two hierarchical ATFMRP model with airway capacity constraints, and conflict-free trajectories can be generated for each flight. Alonso-Ayuso et al. (2012a,b) propose two ATFMRP models based on the airway to address both deterministic and stochastic scenarios. The issue of energy-efficiency has drawn lots of academic attention, but the above works have not considered it.

There has been significant research effort related to sector-based ATFMRP, but the systems still cannot meet the huge demand in the future. One primary reason is that the sector-based airspace configuration imposes restrictions on airspace capacity. In some situations that sector capacity is low, conflicts could still happen, and the workload of air traffic controller is very high. The concept of "Free Flight" intends to transform the air traffic control system from a centralized system controlled by air traffic controller to a distributed system controlled by each pilot to improve system capacity and flexibility. Unfortunately, it is far from legal because no state-of-the-art technologies and procedures could ensure safety in the framework of "Free Flight". With these practical issues, there is

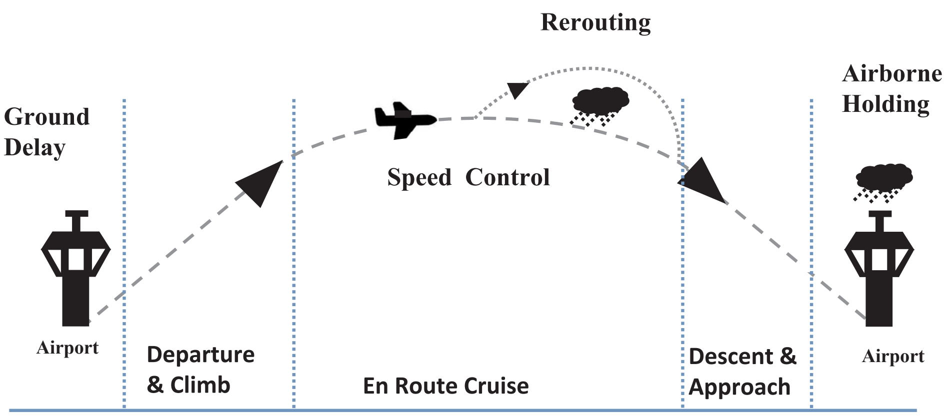

Fig. 2. ATFM tools.