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Optimal aircraft scheduling and routing at a terminal control area during disturbances

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ABSTRACT

This paper addresses the real-time problem of aircraft scheduling and routing in terminal control area. A main task of traffic controllers is to mitigate the effects of severe traffic disturbances on the day of operations in the Terminal Control Area (TCA) of an airport. When managing disturbed take-off and landing operations, they need to minimize the delay propagation and, in addition, to reduce the aircraft travel time and energy consumption. The paper tackles the problem of developing effective decision support tools for air traffic monitoring and control in a busy TCA. To this purpose, centralized and rolling horizon traffic control paradigms are implemented and compared. The mathematical formulation is a detailed model of air traffic flows in the TCA based on alternative graphs, that are generalized disjunctive graphs. As for the aircraft scheduling and (re-)routing approaches, the First-In-First-Out (FIFO) rule, used as a surrogate for the behavior of air traffic controllers, is compared with various optimization-based approaches including a branch and bound algorithm for aircraft scheduling with fixed routes, a combined branch and bound and tabu search algorithm for aircraft scheduling and re-routing, and a mixed integer linear programming formulation for simultaneous scheduling and routing. Various hypothetical disturbance scenarios are simulated for a real-world airport case study, Milano Malpensa, and the proposed timing and routing approaches are compared in terms of their performance in the different scenarios. The disturbed traffic situations are generated by simulating multiple delayed arriving/departing aircraft and a temporarily disrupted runway. In general, the optimization approaches are found to improve the solutions significantly compared to FIFO, in terms of aircraft delay minimization. However, there are some trade-offs involved in picking the right approach and paradigms for practical implementations.

1. Introduction

An increasing problem that air traffic controllers have to face is the growth of traffic demand while the availability of new airport resources is very limited. Aviation authorities are thus seeking methods to better use the infrastructure and to better manage aircraft movements in the proximity of airports, improving aircraft punctuality and respecting all safety regulations (Pellegrini and Rodriguez, 2013).

This paper deals with the development of advanced optimization approaches for improving the real-time management of severely disturbed aircraft operations at busy airports. Terminal area operations are usually considered under the umbrella

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of Air Traffic Control (ATC) because they are managed by local airport controllers. From a logical point of view, ATC decisions in a Terminal Control Area (TCA) can be broadly divided into: (i) Routing decisions, where an origin–destination route for each aircraft has to be chosen regarding air segments and runways; (ii) Timing decisions, where routes are fixed under traffic regulation constraints and an aircraft passing timing has to be determined in each air segment, runway and (possibly) holding circle. In practice, routing and timing decisions in a TCA are taken simultaneously and a given performance index is optimized. The main objective of routing decisions is typically to balance the use of critical resources while that of the whole process is to limit the propagation of disturbances across flight legs either due to aircraft, crew, or passenger considerations (Ball et al., 2007).

Decision Support Systems (DSSs) based on optimization may help to exploit to the fullest the capacity available in a TCA during operations. The improvement of take-off/landing operations is an important factor related to the performance of the entire ATC system. However, ATC decisions are still mainly taken by human controllers with only a limited aid from automated systems (Djokic et al., 2010; Kim et al., 2009; Prevot et al., 2011). In most cases, computer support only consists of a graphical view of the current aircraft position and speed. As a result, delays are not effectively limited during landing and take-off operations. The optimization-based DSS developed in this work may support controllers to dynamically exploit at most the capacity available in the TCA during severe disturbances and busy traffic.

Landing aircraft move along predefined routes from an entrance point in the TCA to a runway following a standard descent profile. During all the approach phases, a minimum separation between every pair of consecutive aircraft must be guaranteed. This standard separation depends on the types and relative positions of the two aircraft (at the same or different altitude). By considering the different aircraft speeds, the safety distance can be translated in a separation time. Similarly, departing aircraft leave the runway moving towards the assigned exit point from the TCA along an ascent profile, respecting separation standards. The runway can be occupied by only one aircraft at a time, and a separation time should be ensured between any pair of aircraft. Once a landing/take-off aircraft enters the TCA it should proceed to the runway. However, airborne holding circles (ground holding) can be used to make aircraft wait in flight (at ground level) until they can be guided into the landing (take-off) sequence. Real-time traffic management copes with potential aircraft conflicts by adjusting the off-line plan in terms of re-timing, re-ordering, re-routing and holding actions. A potential conflict occurs whenever aircraft traversing the same resource (i.e. air segment or runway) do not respect the minimum separation time required for safety reasons. Separation times depend not only on the aircraft sequence but also on the route chosen for consecutive aircraft in each TCA resource and the aircraft types (we consider three aircraft categories: small, medium and large).

The problem of reacting to disturbed traffic conditions is a key issue in air traffic control practice (Prevot et al., 2011; Taylor and Wanke, 2011). This paper focuses on the real-time control problem to provide optimal conflict-free airborne decisions at the TCA. Similar problems are also studied in railway transportation field for re-ordering and re-routing problems (D'Ariano et al., 2008; Pellegrini and Rodriguez, 2013). However, the two types of problems have a quite different structure and require careful adaptation of existing solution frameworks, mathematical models and algorithmic methods.

In previous works of our research group, we developed a branch and bound algorithm for the Air Traffic Control problem in a Terminal Control Area (ATC-TCA) problem with fixed routes, in which aircraft routes are decided at preliminary step (D'Ariano et al., 2010). In a recent work, we developed an iterative approach for solving the ATC-TCA problem with flexible routes (D'Ariano et al., 2012a; D'Ariano et al., 2012b). Given a route for each aircraft, a scheduling approach takes the aircraft sequencing decisions and assigns the start time to each operation. A re-routing approach then searches for better aircraft routes. From our previous research (D'Ariano et al., 2012a), a better performance has been observed when using runway re-routing compared to the re-routing of other TCA resources.

The objective of this work is to investigate the potential delay reduction achievable by optimization-based solvers with respect to the most common approach used in practice for real-time aircraft scheduling and routing at a busy and complex TCA, in presence of severe disturbances and even for large time horizons of traffic predictions. To this aim, this paper presents a number of modeling and algorithmic contributions. The original contributions are the next summarized:

- A new formulation is proposed for the simultaneous aircraft scheduling and routing problem.
- The problem is solved via various solution approaches: 1. a commercial solver, 2. an optimization solver based on a problem decomposition in re-timing, re-ordering and re-routing decisions, 3. a temporal decomposition of the overall problem, 4. a number of combinations of the proposed approaches. Specifically, the approach 2 is based on the algorithms developed by D'Ariano et al. (2010), D'Ariano et al. (2012b), and is extended in the current paper by means of a procedure to speed-up the search of a feasible schedule. The approach 3 was presented in Samà et al. (2013). Approach 4 extends the approach 3 to deal with routing flexibility.
- Three model variants are proposed to study different objective functions and user requirements.
- The three model variants and the various solution approaches are compared in the computational results section. We tested 80 practical-size ATC-TCA instances of the Milano Malpensa airport (including various sources of disturbance and traffic predictions of increasing length). Each instance has been tested for the three model variants and for the various solution approaches.
- The computational results show the high potential of the optimization-based approaches compared to the FIFO rule. The optimization procedures are evaluated in terms of computation time indicators, number of optimal solutions, number of constraint violations and aircraft delay minimization.