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Pre-tactical optimization of runway utilization under uncertainty

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A B S T R A C T

Efficient planning of runway utilization is one of the main challenges in Air Traffic Management (ATM). It is important because runway is the combining element between airside and groundside. Furthermore, it is a bottleneck in many cases. In this paper, we develop a specific optimization approach for the pre-tactical planning phase that reduces complexity by omitting unnecessary information. Instead of determining arrival/departure times to the minute in this phase yet, we assign *several* aircraft to the same time window of a given size. The exact orders within those time windows can be decided later in tactical planning. Mathematically, we solve a generalized assignment problem on a bipartite graph. To know how many aircraft can be assigned to one time window, we consider separation requirements for consecutive aircraft types. In reality, however, uncertainty and inaccuracy almost always lead to deviations from the actual plan or schedule. Thus, we present approaches to incorporate uncertainty directly in our model in order to achieve a stabilization with respect to changes in the data. Namely, we use techniques from robust optimization and stochastic optimization. Further, we analyze real-world data from a large German airport to obtain realistic delay distributions, which turn out to be two-parametric Γ-distributions. Finally, we describe a simulation environment to test our new solution methods.

1. Introduction

ATM systems are driven by economic interests of the participating stakeholders and, therefore, are performance oriented. As possibilities of enlarging airport capacities are limited, one has to enhance the utilization of existing capacities to meet the continuous growth of traffic demand. The runway system is the main element that combines airside and groundside of the ATM System. Therefore, it is crucial for the performance of the whole ATM System that the traffic on a runway is planned efficiently. Such planning is one of the main challenges in ATM. Uncertainty, inaccuracy and non-determinism almost always lead to deviations from the actual plan or schedule. A typical strategy to deal with these changes is a regular re-computation or update of the schedule. These adjustments are performed in hindsight, i.e. after the actual change in the data occurred. The challenge is to incorporate uncertainty into the initial computation of the plans so that these plans are robust with respect to changes in the data, leading to a better utilization of resources, more stable plans and a more efficient support for ATM controllers and stakeholders. Incorporating uncertainty into the ATM planning procedures further makes the total ATM System more resilient, because the impact of disturbances and the propagation of this impact through the system is reduced.

In the present paper, we investigate the problem of optimizing runway utilization under uncertainty. The goal is to incorporate uncertainties into the initial plan in order to retain its feasibility despite changes in the data. We focus on the pre-tactical planning phase, i.e. we assume the actual planning time to be several hours, or at least 30 min, prior to actual arrival/departure times. We develop an appropriate mathematical optimization model for this particular planning phase. The basic idea is that in pre-tactical planning we can reduce the complexity of the problem by not determining an exact arrival/departure sequence in terms of exact landing/take-off times for each aircraft, as we do later in tactical planning. Instead, we answer the question of how many aircraft can be scheduled to one time window of a given size without violating distance requirements. (For example, it is definitely possible to

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assign more than one aircraft to a time window from 12:00 pm to 12:10 pm.) Then, we consider a discretized time horizon consisting of such time windows and assign each aircraft to one of them.

This paper is an extension of Fürstenau et al. (2014), where the authors set up a mixed integer program (MIP) for the pre-tactical optimization of runway utilization. Afterwards, the impact of disturbances on the deterministic solutions was investigated. The results showed that it is crucial to enrich the optimization approach by protection against uncertainties, in order to produce less necessary replanning. In the current paper, we thus incorporate uncertainties directly into the model by using techniques from robust and stochastic optimization. The remainder of this paper is organized as follows: In Section 2, we give an overview over the literature related to runway optimization and explain why our approach is different. We develop the pre-tactical runway optimization model in Section 3. In Sections 4 and 5 we describe our approaches to incorporate uncertainties into this model, and present some computational results in Section 4. In order to be able to test our approaches in a more realistic setting, we analyze real-world delay data from a large German airport in Section 7 (extending the descriptions in Fürstenau et al. (2014)), where we also describe our simulation environment to test current and future solution methods. Finally, we conclude in Section 8.

2. Related work

There are many different approaches that deal with the optimization of runway utilization in the literature. Most of them treat the runway scheduling problem in the tactical planning phase.

2.1. Deterministic approaches

The most cited MIP model in this context is probably the one introduced by Beasley et al. (2000). Their linear objective function minimizes delay, the constraints come from the aircraft dependent separation times. They also present an integer program (IP) formulation where time is discretized, but they don't explore it further because of disappointing computational experiences. Soomer and Franx (2008) consider the problem from an airline point of view. They use Beasley's MIP but allowing airlines to define their own cost functions for each flight. Bertsimas et al. (2011) develop a comprehensive IP for Air Traffic Flow Management which integrates all phases of a flight, different costs for ground and air delays, rerouting, continued flights and cancellations. Kjenstad et al. (2013) state a time-discretized model. They assign an aircraft to a time window and claim that a number of subsequent time windows (dependent on the aircraft type) remains unassigned. In their model, they also consider minimal taxiways and the possibility to drop departures. Their linear objective function minimizes delay and the number of dropped departures.

Many authors use heuristic methods aiming to provide solutions in close to real-time. To schedule aircraft in a first-come first-served order (FCFS) seems to be fair and also reduces the work of traffic controllers. However, such an approach doesn't provide maximal throughput or minimal delay in general (Bennell et al., 2011). Dear (1976) developed the concept of Constrained Position Shifting, were each aircraft can be scheduled only a limited number of steps away from the FCFS sequence. Balakrishnan and Chandran (2010) solved this problem as a shortest path problem on a special network.

Anagnostakis and Clarke (2003) formulate a two-stage heuristic algorithm for the outbound runway scheduling problem. In the first stage, candidate weight class sequences are determined w.r.t. distance requirements, ordered by the corresponding throughput. In the second stage individual aircraft are assigned using operational constraints (e.g. earliest and latest departure times of aircraft).

As mentioned, in our optimization model (described below and in Fürstenau et al. (2014)) we allocate time windows to aircraft. However, though many papers about runway optimization deal with ”slot allocation”, this term is used to describe different problems. Often, it is associated with the Ground-Holding Problem (GHP), where ”slot” means a certain departure time which is assigned to an aircraft. Ball and Dahl Vossen (2009) also address the GHP, but they assign arrival slots to aircraft which provide the corresponding departure delay in hindsight. They consider matchings in a bipartite graph which they call the “flight allocation graph”. The main focus in this paper lies on the graph structure and matching algorithms.

None of the approaches above deal with “slots” as time windows to which *several* aircraft can be assigned. Thus, to the best of our knowledge there is no approach similar to ours in which the pre-tactical planning phase is modelled by assigning such time windows to aircraft.

2.2. Approaches that incorporate uncertainties

All runway optimization approaches presented above assume that all parameters are known with certainty. We found few works where uncertainties are incorporated. However, none of them are using robustness concepts similar to those described in this paper. Chandran and Balakrishnan (2007), e.g., develop an algorithm with Constrained Position Shifting that handles uncertainty in the estimated time of arrival. Hu and Di Paolo (2008) formulate a genetic algorithm and compute solutions disturbing the estimated arrival time of 20% of the aircraft. Sölveling (2012) presents a two-stage stochastic program for solving the mixed-mode runway scheduling problem with uncertain earliest times. In the first stage he determines the weight class sequence. An exact sequence of individual aircraft follows in the second stage.

3. The modeling

As mentioned above, we model the problem of optimizing runway utilization in the pre-tactical planning phase by assigning time windows to aircraft. Throughout this paper, we consider single-mode runways with only arriving aircraft. In the future, we will adjust our models to mixed-mode runways. But since the single-mode problem is already quite complex from a mathematical point of view, we decided to focus on arrivals for now. In our modeling approach we claim that each aircraft has to receive exactly one time window as each aircraft has to be scheduled. On the other hand, the number of aircraft that can be assigned to one time window depends on its size and the weight classes of the aircraft. The underlying idea is that, contrary to tactical planning, we don't need to determine arrival times to the minute yet, because we are several hours (or at least 30 min) prior to the first scheduled time. Thus, the exact arrival sequences within the time windows can be decided later.

In this section, we develop a MIP for the described problem. The objective is the maximization of punctuality. In other words, the deviation from scheduled times in both directions shall be minimized. The MIP constraints consist of general assignment constraints and the modeling of minimal time distance requirement. Those minimum separation times between two consecutive aircraft depend on their corresponding weight classes. Hereof, we consider three different aircraft categories (*Light*, *Medium* and *Heavy*) and use Table 1 (ICAO Document 4444, 2007).

Before we can state our model, we have to analyze the underlying problem structure more precisely.

For each aircraft, we consider several corresponding times:

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