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Scheduling aircraft take-offs and landings on interdependent and heterogeneous runways

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ABSTRACT

This paper presents an optimization method for the aircraft scheduling problem with general runway configurations. Take-offs and landings have to be assigned to a runway and a time while meeting the sequence-dependent separation requirements and minimizing the costs incurred by delays. Some runways can be used only for take-offs, landings, or certain types of aircraft while schedules for interdependent runways have to consider additional diagonal separation constraints.

Our dynamic programming approach solves realistic problem instances to optimality within short computation times. In addition, we propose a rolling planning horizon heuristic for large instances that returns close-to-optimal results.

1. Introduction

Runway systems of major international airports are a bottleneck in the global air traffic network (see, *e.g.*, Balakrishnan and Chandran, 2010; Bennell et al., 2013; Ghoniem et al., 2015). Due to technical restrictions and safety regulations, runway systems only allow a limited number of runway operations (that is, aircraft take-offs and landings) per hour. The total air traffic, however, is growing steadily, and the number of commercial aircraft in use is projected to double within the next two decades (Boeing, 2014). A cost-efficient way to increase the capacity of an existing runway system is to improve its take-off and landing schedules. Thereby, expensive investments in additional runways or airports could be averted or postponed.

The *aircraft scheduling problem* (ASP) can be defined as follows. One set of aircraft is at the gates or on the airfield and is preparing for take-off. Another set of aircraft is approaching the airport by air and is preparing to land. Each aircraft belongs to an aircraft class based on its size and weight, and has a target time for its take-off or landing within a time window. The decision problem at hand is to assign a runway and a take-off or landing time to each aircraft. The resulting runway schedule has to meet separation requirements that are sequence-dependent, as they depend on the operation type, *i.e.*, take-off or landing, and the respective aircraft class of both the preceding and succeeding operation. When an operation is delayed, a delay penalty cost is incurred that depends on the respective operation class, *i.e.*, operation type and aircraft class, and on the length of the delay.

To ensure the necessary separation between runway operations on the same runway, international aviation authorities, such as the FAA (Federal Aviation Administration) and ICAO (International Civil Aviation Organization), define separation requirements for three aircraft classes (small, large, heavy) (see, for example, Table 1a). Note that between two take-offs

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and between two landings, the separation matrix fulfills the triangle inequality. However, when the operation type changes, the triangle inequality is not fulfilled. Consider, for example, the sequence *heavy landing – small take-off – small landing:* The earliest time for the small landing is restricted not by the preceding take-off but by the heavy landing. Thus, when scheduling both take-offs and landings, the separation has to be ensured between all pairs of runway operations. This constraint is referred to as complete separation (Beasley et al., 2000).

We consider general assumptions concerning the airport's runway system that were not previously considered. Many major international airports, such as Frankfurt Airport (the largest German airport) operate runways that are *heterogeneous, i.e.*, not all operations can be performed on all runways, or *interdependent, i.e.*, the operations on one runway also restrict the operations on the other(s). Table 1b shows the separation constraints for parallel runways depending on their spacing. Ashford et al. (2011) give detailed information on the runway specifications required to accommodate certain types of runway operations.

The planning horizon of the ASP is very short: we consider aircraft approaching the airport as soon as they enter the "Extended Terminal Maneuvering Area" (E-TMA) of the airport, approximately 30 to 40 min prior to their target landing time. This area has a radius of up to 40 nautical miles and is controlled by "Terminal Radar Approach Control" (TRACON) (Bennell et al., 2013). We assume to have precise and reliable data on the aircraft on the airport's airfield and in the E-TMA, that is, we have a static and deterministic problem setting. Landing times can be assigned to the approaching aircraft before they reach the final approach path, approximately 20 min before landing. This short planning horizon necessitates a fast solution approach that calculates runway schedules in close to real-time to be of practical use.

Although the ASP has been addressed in many scientific papers, the literature review in Section 2 shows that research on the ASP with both heterogeneous and interdependent runways is scarce. Most papers assume either independent or homogeneous runways, or they restrict themselves to heuristic solution approaches. In this paper, we propose a dynamic programming (DP) approach that derives optimal runway schedules for realistic runway configurations. To solve large problem instances, we also propose a rolling planning horizon (RPH) heuristic that divides a large ASP instance into a number of smaller but connected instances that are then iteratively solved. The main contributions of this paper can be summarized as follows.

- We present a DP-based optimization approach for scheduling runway operations with non-triangular separation times and with interdependent and heterogeneous runways.
- We analyze the efficiency of the proposed approach in a numerical study using realistic data sets and runway systems. For large problem instances, we propose a rolling planning horizon heuristic that yields close-to-optimal results.
- We show the benefit of runway scheduling compared to first-come-first-served (FCFS). Optimized runway schedules are able to handle additional runway operations while still reducing delays.

The remaining part of this paper is organized as follows. In Section 2, we give an overview of related research articles. In Section 3, we describe the model of the ASP with interdependent and heterogeneous runways and formulate a mixed-integer program (MIP). We present the proposed exact solution approach in Section 4 and the heuristic approach in Section 5. We

Table 1
Separation requirements (in seconds).

(a) Separation for operations on the same runway

			Trailing aircraft					
			Landing			Take-off		
			Small	Large	Heavy	Small	Large	Heavy
Leading aircraft	Landing	Small	82	69	60	75	75	75
		Large	131	69	60	75	75	75
		Heavy	196	157	96	75	75	75
	Take-off	Small	60	60	60	60	60	60
		Large	60	60	60	60	60	60
		Heavy	60	60	60	120	120	90

Source: *e.g.*, Balakrishnan and Chandran (2010) and Farhadi et al. (2014)

(b) Separation for operations on parallel runways

Runway spacing	Take-off → Take-off	Take-off → Landing	Landing → Take-off	Landing → Landing
Up to 2500 ft (up to 760 m)	As on single runway	As on single runway	Independent (no separation)	As on single runway
2500–4300 ft (760–1310 m)	Independent	Independent	Independent	40 s
More than 4300 ft (more than 1310 m)	Independent	Independent	Independent	Independent

Source: De Neufville and Odoni (2013)