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# Scheduling models for optimal aircraft traffic control at busy airports: Tardiness, priorities, equity and violations considerations ☆

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ABSTRACT

This work addresses the real-time optimization of take-off and landing operations at a busy terminal control area in case of traffic congestion. Terminal areas are becoming the bottleneck of the entire air traffic control system, in particular in the major European airports, where there is a limited possibility to build new infrastructure. The real-time problem of effectively managing aircraft operations is particularly challenging, since it is necessary to incorporate the safety regulations into the optimization model and to consider numerous performance indicators that are important to compute good quality solutions. However, in practice there is no well-recognized objective function and traffic controllers often use simple scheduling rules. In this paper, mixed integer linear programming formulations are proposed to investigate the trade-off between various performance indicators of practical interest, while taking into account the safety constraints with a high modeling precision. Experiments are performed for the two major Italian airports, Milano Malpensa and Roma Fiumicino, by simulating various sets of random landing and take-off aircraft disturbances. Practical-size instances are solved to (near)optimality via a commercial solver. The optimized solutions are also compared with a commonly used scheduling rule. A comprehensive computational analysis makes possible the selection of those solutions that are able to find a good compromise among the various indicators and, consequently, the investigation of the most representative formulation.



## 1. Introduction

The ever growing demand of air transport is increasing the pressure on air traffic controllers, since air traffic in peak hours is getting closer to the capacity of the Terminal Control Area (TCA), at least in the major European airports where there is limited possibility of creating new infrastructure. Aviation authorities are thus seeking optimization methods to better use the available infrastructure [4,5,21,27,45]. However, the development and the implementation of effective optimization methods for such operational problems require the consideration of a number of aspects that are rarely taken into account simultaneously in the related scheduling theory:

- The optimization model should be able to incorporate all detailed information that is compliant with the safety regulations of the TCA, including information which is not relevant for the air traffic flow management in large networks with multiple airports and is therefore neglected in macroscopic models [17,22,48]. In most of the macroscopic models, the characteristics of the airport infrastructure are drastically simplified and the flight paths are aggregated, so that *potential conflicts* between single aircraft may not be visible, at least at the level of runways, ground and air segments of the TCA. A potential conflict occurs whenever aircraft traversing the same resource do not respect the minimum required safety distance.
- The time available for developing a new schedule of take-off and landing aircraft in the TCA can be very limited, since a computerized scheduler should be able to promptly react to any significant change occurring during operations.
- To a large extent, air traffic control operations and related issues are still scheduled by human controllers, who develop feasible aircraft schedules in the TCA based on their past experience, intuition and some scheduling rules without using any formally defined performance indicator. Recently, the push from SESAR and for CDM compliance [36] is making this less common though and airports have at least some automated support systems for some of the operations. For example, different commercial arrival manager systems are used at various airports [42,74]. However, the controllers usually have to fine tune the arrivals sequencing coming out of the systems themselves at

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the moment, since these systems do not usually (fully) take into account the fine details of the aircraft movement required to land in the correct order. Furthermore, we believe that further automated support is required in order to compute alternative (near)optimal ASP solutions and evaluate them in terms of a number of performance indicators in a short-term. In fact, the existing arrival manager systems incorporate various performance indicators that need to be fine tuned across all airports. The lack of a generally recognized performance indicator to optimize places importance on the definition of acceptable objective functions. The quality of scheduling aircraft in the TCA typically involves several performance indices reflecting the interests of the different actors involved in air traffic management, such as the aircraft punctuality, the utilization level of airport resources, the costs incurred by different airline companies in terms of delays, broken flight connections and energy consumption, and so on. All these indices should be taken into account in the schedule development phase.

This paper addresses the first item by developing mixed integer linear programming (MILP) formulations, that take into account the relevant TCA safety aspects and various performance indicators with a high level of detail. As shown in the survey of Bennell et al. [18], the aircraft scheduling literature presents numerous models of the independent runway sequencing problem. This problem is modelled as a single machine scheduling problem. A natural way to model and solve a more accurate and extended aircraft scheduling problem with interdependent runways and air segments of the TCA is via job shop scheduling. The latter type of modelling approach permits to consider the airspace interactions between aircraft in order to compute better quality aircraft scheduling solutions in terms of delay management and traffic flow coordination in the TCA.

The MILP formulations proposed in this paper can be considered as a generalization of existing job shop scheduling models with blocking (no-store), no-wait and other additional constraints. These models are known under the name *generalized disjunctive graph* or *alternative graph*. Previous research on those job shop scheduling models has been successfully applied to model and solve complex benchmark instances on job shop scheduling [39,55–57,62], railway traffic management problems [25,50,52], and air traffic management problems [20,27,28,65,66].

The second item suggests that optimization models with a single objective function are more suitable than multi-objective approaches, since more efficient tools are available to solve these problems. This is also the most common choice in the literature (see, e.g., the reviews in [14,18,24,46,48,61]).

The present paper investigates MILP formulations with single objective functions in order to find a good compromise among the different indices listed in the third item. Specifically, we observe that aircraft typically flies at constant speed in the TCA and that at constant speed the energy consumption is almost proportional to the flying time. We use the aircraft flow time as a surrogate of the energy consumption. Also, we adopt makespan-like objective functions in order to minimize the maximum completion time (i.e. the arrival time of the last aircraft), as a common surrogate for the throughput maximization, or the maximum tardiness (i.e. the largest aircraft delay). Moreover, we implicitly take into account the minimization of broken flight connections by minimizing the number of aircraft delayed more than a given threshold. All performance indicators can be measured in terms of aircraft arrival times at the entrance of the TCA and at the runways.

The aircraft scheduling problem (ASP), we deal with in this paper, can be summarized as follows. Given a set of landing/take-off aircraft and for each aircraft its path in the TCA, its current position, its scheduled runway occupancy time and the required time window to accomplish the arriving/departing procedures, the ASP is to assign the start time to each aircraft in all the resources it crosses in its path in such a way that all the potential conflict situations between aircraft are solved (at a microscopic level) and a suitable objective function is minimized.

This work follows the approach of Bianco et al. [20], based on the no-wait version of the job shop scheduling problem. However, this paper is based on the alternative graph model introduced by Mascis and Pacciarelli [55], that is able to model the ASP with an increased level of detail. The higher modeling precision includes further relevant TCA aspects such as holding circles, waiting in flight before landing, traveling in feasible time windows, hosting multiple aircraft simultaneously in air segments and individual aircraft simultaneously in runways. Previous works based on the alternative graph model of the ASP have been proposed recently [26–28,65,66]. D'Ariano et al. [26,28] deal with the development of a branch and bound algorithm for the ASP. D'Ariano et al. [27] extend the ASP to a routing and scheduling problem and solve it with a tabu search algorithm. Samà et al. [65,66] develop a rolling horizon approach for the original and extended ASP. However, all these works deal with the minimization of a makespan-like objective function.

The contribution of this work is to generalize the work done on the ASP modelled via alternative graphs. We investigate microscopic MILP formulations of the ASP with different objective functions and examine the differences between the ASP solutions in terms of various performance indicators. As far as we know, the proposed formulations increase the level of detail regarding the modeling of the constraints in the airspace nearby the TCA compared to the existing models, and permit to deal with any kind of objective function and constraint. We believe that the investigation of a suitable formulation of the ASP, that takes into account several performance indicators and models the constraints with high precision, is still an open problem in the related literature.

A computational study is presented for assessing the practical applicability of the proposed formulations. The ASP solutions are analyzed from the viewpoint of the above described performance indicators and trade-off between them, while previous research often focuses on a single performance indicator, with a myopic view in terms of other possible performance indicators. A procedure is proposed to develop a *combined formulation* with a good trade-off performance on several indicators.

The experiments have been carried out on the main Italian airports in terms of passenger flows: Roma Fiumicino (FCO) and Milano Malpensa (MXP). Regarding the air traffic disturbances, 40 randomly delayed scenarios are considered for practical-size instances. The resulting problems are solved with a commercial solver to (near)optimality for each ASP formulation. The optimized solutions are also compared with the solutions computed by a practical scheduling rule.

Section 2 reviews the literature most relevant for this work. Section 3 formally describes the modelling of specific ASP constraints. Section 4 presents the mathematical formulations. Section 5 reports the experiments conducted on the FCO and MXP instances. Section 6 summarizes the paper results and outlines future research directions. Two appendices illustrate the alternative graph modeling and solving for a numerical ASP example.

## 2. Literature review

This section briefly reviews recent papers on some aspects of the air traffic flow management (ATFM) problem. We present various ATFM literature classifications and discuss our contribution. A more general discussion of the existing literature can be found e.g. in [1,14,18,24,33,46,48,61].

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