Transportation Research Part D 63 (2018) 872–889

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Optimization of terminal airspace operation with environmental considerations

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ARTICLE INFO

Keywords:
Aviation emissions and noise
Terminal airspace
Approach
Multi-objective optimization

ABSTRACT

The rapid growth in air traffic has resulted in increased emission and noise levels in terminal areas, which brings negative environmental impact to surrounding areas. This study aims to optimize terminal area operations by taking into account environmental constraints pertaining to emission and noise. A multi-objective terminal area resource allocation problem is formulated by employing the *arrival fix allocation* (AFA) problem, while minimizing aircraft holding time, emission, and noise. The NSGA-II algorithm is employed to find the optimal assignment of terminal fixes with given demand input and environmental considerations, by incorporating the *continuous descent approach* (CDA). A case study of the Shanghai terminal area yields the following results: (1) Compared with existing arrival fix locations and the first-come-first-serve (FCFS) strategy, the AFA reduces emissions by 19.6%, and the areas impacted by noise by 16.4%. AFA and CDA combined reduce the emissions by 28% and noise by 38.1%; (2) Flight delays caused by the imbalance of demand and supply can be reduced by 72% (AFA) and 81% (AFA and CDA) respectively, compared with the FCFS strategy. The study demonstrates the feasibility of the proposed optimization framework to reduce the environmental impact in terminal areas while improving the operational efficiency, as well as its potential to underpin sustainable air traffic management.

1. Introduction

With the significant growth of air transportation over the past decades, the associated environmental impacts have become a major concern to the public and authorities (Amato et al., 2010; Kurniawan and Khardi, 2011; Kinsey et al., 2011). When aircraft fly at low altitudes, e.g. in terminal airspace, they tend to negatively impact the environment and public health (Dolan and Fujiwara, 2016). The terminal airspace provides capacity for arrival and departure routes that connect the runway(s) to the arrival and departure fixes. The mismatch of supply and continuously increasing demand has caused significant congestion at air traffic networks, especially at main bottlenecks such as the terminal airspace (Allroggen and Malina, 2014; Sidiropoulos et al., 2017). A lot of efforts have been dedicated by researchers and practitioners alike to the optimization of operations in the terminal area to alleviate congestion, improve operational efficiency, and reduce environmental impact of air traffic.

The environmental impact of aircraft activities in the terminal area is primarily attributed to the emission of greenhouse gases, pollutants and noises, which are highly related to public health given the relatively low altitude. The emission of pollutants is caused by incomplete combustion of fuel in the engine, which affects local air quality (Carslaw et al., 2008; Dodson et al., 2009; Barrett et al.,

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https://doi.org/10.1016/j.trd.2018.06.018

Available online 01 August 2018

Nomenclature

ATM	Air Traffic Management
AFA	Arrival Fix Allocation
ANP	Aircraft Noise and Performance
CDA	Continuous Descent Approach
ETA	Extended Terminal Area
FAA	Federal Aviation Administration
FBRP	Flow Based Route Planner
FCFS	First Come First Served
FF	Fuel Flow
GA	Genetic Algorithm
GB	National Standard
ICAO	International Civil Aviation Organization
ISA	International Standard Atmosphere
NPD	Noise Power Distance
RNP	Required Navigation Performance
STAR	Standard Instrument Arrival Route
SID	Standard Instrument Departure Route
WECPNL	Weight Equivalent Continuous Perceived Noise Level

2013; Masiol and Harrison, 2014; Płanda and Skorupski, 2017), leading to adverse effect to the natural environment and public health (Kampa and Castanas, 2008; Barrett et al., 2012, 2015; Penn et al., 2017). Noise pollution, with the sound reaching 40 dB and above, has been of widespread concern due to its impact on residential areas near the airport (Howarth and Griggs, 2013). High-volume noises can be irritating, affect daily life, and even have negative health effects (Clark and Stansfeld, 2011; Fujiwara et al., 2017; Rodríguez Díaz et al., 2017).

Aiming at the optimization of terminal airspace operation, existing studies tend to focus on the following aspects: runway allocation optimization, traffic flow sequencing, aircraft performance adjustment and terminal resource allocation. We provide a brief overview of these approaches below.

Regarding runway allocation optimization, Carr et al. consider the airlines' priorities to optimize arrival queues, which could reduce the economic impact of ATM restrictions and lead to increased airline economic efficiency by allowing airlines to have greater controls over their individual arrival banks of aircraft (Carr et al., 1999, 2000). Anagnostakis et al. (2001) establish a two-stage stochastic optimization model based on airport ground operation, with a focus on runway operations specifically for departure traffic. Sölveling et al. (2011) find that optimization-based scheduling with explicit environmental considerations tend to produce significant benefits for both airlines and society. Yin et al. (2014a,b) put forward an optimization method for multi-runway spatio-temporal resource scheduling regarding the modes of dependent approaches and independent departures, which could significantly improve the service quality at busy airports.

On traffic flow sequencing, Bianco et al. (2006) propose a job-shop scheduling model with sequence-dependent setup times and release dates to coordinate both inbound and outbound traffic flows on all the predetermined routes of an airport terminal area and all aircraft operations at the runway complex. Balakrishnan and Chandran (2006) consider the problem of scheduling arrival aircrafts in a constrained position shifting environment and present a dynamic programming approach to maximize runway throughput. Based on the aircraft data total-energy model, Jin et al. (2013) establish an analytical relationship between speed, altitude, and fuel burn. The theoretical analysis suggests that speed profile has an impact on the fuel consumption as much as, if not more than, vertical profile in the terminal area. Kim et al. (2014) present an optimization model for simultaneously assigning aircraft to runways and scheduling the arrival and departure operations on those runways, to minimize the total emissions produced in the terminal area and on the airport surface.

Regarding aircraft performance adjustment, Mitchell et al. (2012) study the trade-off between CO_2 and noise. The authors compared aircraft departure procedures subject to speed constraints with a free-flow scenario, and the results suggest that CO_2 emissions could be reduced by 180 kg per flight if all the departure speed constraints were removed at a cost of increased noise exposure below 70 dB. Silva et al. (2013) investigate the environmental impact of Required Navigation Performance (RNP) procedures, which seeks to improve fuel efficiency and reduce emissions by allowing noise to be concentrated in some areas near the airport. Marais et al. (2013) qualitatively describe measures to mitigate the environmental impact in each flight phase. Zhang et al. (2014) propose a noise assessment method based on track segment combined with civil aircraft motion model and performance model. Koudis et al. (2017) analyses the impact on fuel consumption and pollutant emissions by using reduced thrust takeoff. Ashok et al. (2017) calculate the minimum air quality and environmental impacts beyond fuel burn and CO_2 minimization by optimizing gate holding and de-rated takeoffs.

Finally, regarding terminal resource allocation, Prete and Mitchell (2004) develop a Flow-Based Route Planner (FBRP) system, which could handle a variety of constraints and efficiently route multiple flows of aircraft in dynamic weather scenarios. Given a flight route through the terminal area, Pfeil (2011), Pfeil and Balakrishnan (2012) apply machine learning techniques to optimize terminal area operations, by dynamically re-locating arrival and departure routes to maximize the expected capacity of the terminal area. In order to improve terminal operation efficiencies, Chen et al. (2013) present an algorithm for the integrated design of dynamic arrival and departure weather avoidance routing within extended terminal airspaces, Simaiakis et al. (2014) demonstrate the reduction of airport congestion through pushback rate control. Wan et al. (2016) establish an optimization model of arrival and departure resource allocation in terminal areas by considering factors such as airspace capacity and safety interval.

Attempts to mitigate environmental impacts of terminal airspace operation tend to focus on individual aircraft flight profiles (i.e. at a microscopic level). There is a lack of macroscopic modeling and optimization methods that aim to reduce the emission and noise in the entire terminal area. In this paper, we develop a multi-objective optimization framework based on *arrival fix allocation* (AFA) and *continuous descent approach* (CDA), aiming at reducing the congestion and environmental impacts of terminal operation under normal and adversarial weather conditions. To address the operation bottlenecks in the terminal area, we propose a concept to