Journal of Air Transport Management 73 (2018) 120–133

Contents lists available at ScienceDirect

Journal of Air Transport Management

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

Minimizing airline and passenger delay cost in airport surface and terminal airspace operations

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ARTICLE INFO

Keywords:
Airport surface
Terminal airspace
Airlines and passengers preferences
Integrated operations
Air traffic control

ABSTRACT

This research studies the effectiveness of incorporating airline and passenger delay cost (APDC) into an integrated airport surface and terminal airspace (ASTA) traffic management system. Most air traffic management systems typically schedule aircraft with an assumption that all flights want to be operated along the minimum fuel trajectory. However, airlines and passengers may have other preferences that can significantly influence flight schedules. Therefore, the objective of this research is to investigate the effect of incorporating APDC to ASTA scheduling, while ensuring safety. A mixed integer nonlinear programming model (MINLP-APDC) and a swap separation violating aircraft heuristic model (SSVA-APDC) are developed to minimize the cost of delays for airlines and passengers. The proposed approaches are compared to the first-come, first-serve heuristic and two integrated scheduling algorithms for ASTA operations: 1) minimizing runway makespan (MINLP-RM); and 2) minimizing flight delays (MINLP-FD). The experimental results show that the proposed approaches save at least 1.2% APDC compared to other approaches. The proposed approaches can also achieve at least 3.0% fewer flight delays than the MINLP-RM model without increasing either runway or schedule makespan. Compared to MINLP-FD, the MINLP-APDC model increases flight delays by on average 3.7% while the SSVA-APDC model achieves on average 15.1% more flight delays. Although the MINLP-APDC model outperforms the SSVA-APDC heuristic in terms of APDC and flight delays, it requires more than 30 min of computational time. Meanwhile, the SSVA-APDC heuristics requires only a few seconds to provide a feasible flight schedule, which makes it more practical.

1. Introduction

Airport surface and terminal airspace (ASTA) operations form one of the largest sets of bottlenecks in the National Airspace System (NAS) as many aircraft operate in a relatively small area in a brief time period (Zelinski, 2014). Several decision support systems and strategies are currently used to schedule aircraft ASTA operations and to better match the capacity of the system. Most of these decision support systems focus on scheduling arrival, departure, and surface operations independently, causing the optimal or near-optimal flight schedule of one operation to be treated as a hard constraint when scheduling the other operations (Lee and Balakrishnan, 2012; Eun et al., 2017). Although the segregation between operations simplifies the scheduling process, it may result in an inefficient use of shared resources and reduces system flexibility due to imposing altitude constraints and directing aircraft to use longer departure and arrival routes (Bosson et al., 2015; Xue and Zelinski, 2015). These inefficiencies can be alleviated by integrating the schedule of ASTA operations. According to Aponso et al. (2015), the goals of the integrated schedule are summarized in three points: 1) providing an accurate and robust information and advisories about traffic flow, 2) reducing uncertainties and maximize the efficiency of operations, and 3) ensuring equitable management of operations and incorporate different NAS stakeholders' preferences.

Most decision support systems do not consider airline or passenger delay cost when scheduling ASTA operations. Aircraft are still guided based on air traffic controllers (ATCs) past experience and intuition, where they focus mainly on reducing the total time spent by the aircraft in the terminal maneuvering area (TMA) (D'Ariano et al., 2015; Samà et al., 2015). As a result, ATCs should give priority to an early departure or arrival aircraft that enters the TMA before a delayed aircraft, which causes the delayed aircraft to be delayed further, increases fuel consumption, and disrupts passengers. Additionally, most of the research conducted on the integrated scheduling of ASTA operations focuses only on minimizing delay without considering the cost of delays. Even though, the cost of delay is not linear with respect to the delay, and the cost of delay imposed on airlines differs from the one experienced by

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https://doi.org/10.1016/j.jairtraman.2018.07.001
Received 21 March 2018; Received in revised form 6 July 2018; Accepted 8 July 2018
0969-6997/

passengers (Ball et al., 2010; Cook and Tanner, 2015). Therefore, this research aims to study the effect of incorporating the delay cost into the integrated scheduling of ASTA operations.

It is assumed in this research that all aircraft arrive and depart through pre-defined routes, and airlines are willing to share their passenger and cost information. A mixed integer nonlinear programming (MINLP) model and a swap separation violating aircraft (SSVA) heuristic are developed to find the aircraft sequence, schedule, and speed that minimizes airline and passenger delay cost (APDC) for ASTA operations. The APDC in this research includes passenger, fuel, crew, and maintenance costs. The effectiveness of the proposed approaches is evaluated using three different flight scenarios data of John F. Kennedy airport. A sensitivity analysis is also performed to examine the effects of the changes in cost parameter on the flight schedule, delays, and runway makespan. The results of the proposed approaches are compared with the first-come, first-serve (FCFS) heuristic and two integrated scheduling algorithms for ASTA operations: 1) minimizing runway makespan; and 2) minimizing flight delays.

The remainder of this paper is organized as follows: a literature review on the scheduling of ASTA operations is summarized in Section 2; the methodology to solve the aircraft scheduling problem is presented in Section 3; the experiment settings and results discussion are in Sections 4 and 5, respectively; lastly, conclusions and future work directions are presented in Section 6.

2. Literature review

Recent research has studied the integration among arrival, departure, and surface operations to improve the use of shared resources. A multistage stochastic programming model was developed to minimize total earliness and tardiness of flights and solved using a sample average approximation method (Bosson et al., 2015). Non-dominated Sorting Genetic Algorithm and Monte Carlo simulation were used to manage runway and surface operations under uncertainty and formulated as a multiple-objective optimization model to minimize both controller intervention count and flight delays (Xue and Zelinski, 2015). A four-hour traffic scenario with a total of 315 flights was built for the Los Angeles International Airport. Their results showed that under different sliding windows, the dynamic stochastic model is capable of reducing total flight delays by 50–150 min for 315 flights with respect to FCFS heuristic, at the same intervention level. A mixed integer programming model and sequencing heuristic approach are proposed to minimize the weighted sum of taxi times and completion time of aircraft ground movements and runway operations (Guépet et al., 2017). The proposed approaches determine the time an aircraft takes off or lands, and the time an aircraft is pushed back or parks into a gate. A simulation-based approach is developed for assessing the benefits of implementing the Airspace Technology Demonstration 2 (ATD-2) system, which is developed by the National Aeronautics and Space Administration (NASA) for integrating ASTA operations. The system is evaluated using operational data from three airports, including Newark Liberty International, Dallas Fort Worth International, and Charlotte/Douglas International Airports (Saraf et al., 2017). The experimental results show that the ATD-2 simulation reduces the average total delay by 33.3% compared to the actual day operations, and approximately 50% of the total delay experienced at gates or in taxi. The research on the integrated scheduling of ASTA has focused mainly on minimizing schedule makespan or flight delays without considering airline and passenger delay, including missed connections and the additional cost of fuel, crew, and maintenance.

Three main reasons for not considering the cost of delays during the scheduling ASTA operations are 1) the inherent difficulties in quantifying flight delays because airlines are not willing to share their sensitive business data, including their operational cost, the number of passengers on each flight, and the number of transfer passengers, 2) the difficulty of selecting metrics that guarantee equity among competing airlines, and 3) air traffic controllers, who are responsible for managing flights, are mainly concerned about safety, airport throughput, and their workload, but they do not consider the profits of airlines. However, a methodology was proposed and data were collected for estimating the components of airline delay costs for various segments of a scheduled flight (Cook et al., 2004). The delays are divided into less than 15 min (short delays) and greater than 65 min (long delays). Their model calculates airline delay cost in terms of fuel, maintenance, fleet, crew, and passenger costs when aircraft are at gate, taxiing, en route, and landing delays. The delay cost for domestic US airlines was estimated using Cook et al. (2004) cost model (Ferguson et al., 2013). The coefficients for the cost factors are updated using US airline cost data to better estimate the delay cost. Additionally, the cost model proposed by (Cook et al., 2004) was extended in (Cook and Tanner, 2015). The cost of passenger delay to the airline was represented as a function of delay duration, instead of treating the short delays to zero and having one multiplier for the long delays. The crew cost was extended to include crew payment schemes and overtime rates, and overhead cost is included in the maintenance cost.

3. Methodology

Let I be a set of aircraft to be scheduled on a set of shared waypoints W, where $i \in I$ and $w \in W$. Each aircraft i needs to cross an ordered set of waypoints to reach its destination, and these waypoints define a route Q_i. The Euclidean distance between waypoint w and the next waypoint $w + 1$ in the route Q_i is denoted by $l_{w,w+1}$. The aircraft speed along the segment of waypoints w and $w + 1$, denoted by v_{iw}, must be within a range of allowable limits $[v_{iw}^{\min}, v_{iw}^{\max}]$ when it reaches waypoint w. The speed variable v_{iw} is assumed to be constant along $l_{w,w+1}$, and aircraft i can change its speed to v_{iw+1} immediately when crossing waypoint $w + 1$. The estimated time for aircraft i to fly or taxi $l_{w,w+1}$ without any separation from other aircraft (unimpeded cross time) is denoted by u_{iw}, whereas the scheduled time for aircraft i to cross waypoint w is denoted by t_{iw}. Moreover, each predefined route Q_i starts with a surface or airspace entry waypoint e_i and ends with an airspace or surface exit waypoint x_i. Aircraft i cannot cross its entry waypoint e_i before a release time r_i and need to be at its exit waypoint at due time d_i. Additionally, the amount of delay that can be absorbed in the air without extra fuel consumption by departure aircraft i, where $i \in D$, is denoted by R_i.

Let a binary variable b_{ijw} denote aircraft sequence at waypoint w, where $b_{ijw} = 1$ if aircraft $i \in I$ precedes aircraft $j \in I$ at waypoint w, and $b_{ijw} = 0$ otherwise. The minimum separation distance between any pair of aircraft at airspace and surface waypoints is denoted by s_{ijw}, where aircraft i precedes aircraft j, while the minimum separation time at runway $k \in W$ is denoted by s_{ijk}, where aircraft i precedes aircraft j at runway k. During traffic congestion, arrival aircraft holds in flight at one of the holding pattern waypoints, where w is in a holding pattern set H. The time required to fly a complete circle is denoted by m_i, and the number of circles to fly is denoted by h_i. When a gate conflict occurs, arrival aircraft must wait for a gate clearance time p_i to arrive at its assigned gate x_i only after it is vacated. The gate clearance time includes aircraft pushback time and the taxi time on the last taxiway segment near the gate. Arrival aircraft i also must wait at least a turnaround time o_i to depart again from its assigned gate.

For APDC, the total number of who check in at an airport (origin passengers) and those whose final destination is the airport (destination passengers) are represented by N_i^o and N_i^d, respectively. The delay cost coefficient for origin and destination passengers aircraft is denoted by α_i. Meanwhile, the number of transit passengers in aircraft i is denoted by N_i^c, and the airline's compensation cost for missed connection per passenger is denoted by β_i. The fuel cost coefficient per gallon is denoted by γ_i, and the fuel burn rates for taxiing and flying aircraft are represented by δ_i^s and δ_i^a, respectively. λ_i denotes the crew cost per minute for aircraft i, and μ denotes the weight of additional crew cost.