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A fuzzy approach to addressing uncertainty in Airport Ground Movement optimisation[☆]

Alexander E.I. Brownlee[a,*], Michal Weiszer[b], Jun Chen[b], Stefan Ravizza[c], John R. Woodward[d], Edmund K. Burke[d]

[a] Division of Computing Science & Mathematics, University of Stirling, UK
[b] School of Engineering and Materials Science, Queen Mary University of London, UK
[c] IBM Global Business Services, Zurich, Switzerland
[d] School of Electronic Engineering and Computer Science, Queen Mary University of London, UK

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ABSTRACT

Allocating efficient routes to taxiing aircraft, known as the Ground Movement problem, is increasingly important as air traffic levels continue to increase. If taxiways cannot be reliably traversed quickly, aircraft can miss valuable assigned slots at the runway or can waste fuel waiting for other aircraft to clear. Efficient algorithms for this problem have been proposed, but little work has considered the uncertainties inherent in the domain. This paper proposes an adaptive Mamdani fuzzy rule based system to estimate taxi times and their uncertainties. Furthermore, the existing Quickest Path Problem with Time Windows (QPPTW) algorithm is adapted to use fuzzy taxi time estimates. Experiments with simulated taxi movements at Manchester Airport, the third-busiest in the UK, show the new approach produces routes that are more robust, reducing delays due to uncertain taxi times by 10–20% over the original QPPTW.

1. Introduction

The aviation industry is experiencing sustained and long-term growth. It is estimated that air traffic within the European Union will reach 1.5× 2012 levels by 2035 (EUROCONTROL, 2013). As a result, many airports are operating near capacity, and the European Commission has recognised (European Commission, 2011) the need to use existing infrastructure more efficiently as well as increasing capacity. Thus, there is increasing interest in better-performing decision support systems to optimise various airport operations (Atkin, 2013). Such systems need to cope well with the complex, integrated nature of airports, and model the processes realistically with minimal simplification of the constraints or uncertainties.

At many airports, a major bottleneck is the system of taxiways between the runways and stands. Optimisation of the Ground Movement of aircraft on the taxiways is a critical problem (Atkin et al., 2010). It directly links other problems such as runway sequencing (Bennell et al., 2011; Sölveling and Clarke, 2014) and stand/gate allocation (Dorndorf et al., 2007; Dell'Orco et al., 2017). Furthermore, while only a fraction of the total journey consists of Ground Movement, it makes a large contribution to the running cost and emissions of an aircraft. Jet-engines are designed to operate optimally at cruising speed in the air, and are considerably inefficient while propelling an aircraft at low speed on the ground. It is estimated that fuel burn during taxiing alone represents up to 6% of airline fleet fuel consumption for short-haul flights with single-aisle aircraft from congested airports, resulting in 5 m tonnes of

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[*] Corresponding author.
E-mail address: sbr@cs.stir.ac.uk (A.E.I. Brownlee).

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fuel burnt globally(Honeywell, 2013), with reduced taxi delays offering potential savings of one third of that (Hao et al., 2017). Reviews of Ground Movement research can be found in Atkin (2013) and Atkin et al. (2010), with work published since these reviews including (Jiang et al., 2013; Yin et al., 2012; Koeners and Rademaker, 2011; Pfeil and Balakrishnan, 2012; Khadilkar and Balakrishnan, 2014; Ravizza et al., 2014; Lee and Balakrishnan, 2012; Simaiakis and Balakrishnan, 2016; Truong, 2012; Simić and Babić, 2015; Guépet et al., 2016; Evertse and Visser, 2017; Zhang et al., 2015; Yu et al., 2017; Behrends and Usher, 2016; Guépet et al., 2017; Morris et al., 2016; Stergianos et al., 2016; Yang et al., 2017).

A critical issue remaining largely unaddressed by existing research (notable exceptions being (Lee and Balakrishnan, 2012; Koeners and Rademaker, 2011)) is the uncertainty inherent in Ground Movement. In particular, it is hard to accurately predict the time taken to travel between the runways and stands. This can be affected by slope, turning angle, other aircraft, runway crossings and simply the speed set by the flight crew. Existing approaches to Ground Movement optimisation typically assume that the taxi times are fixed. This can lead to a lack of robustness: an aircraft arriving at a point before or after the expected time can cause conflicts with other aircraft, leading to delays. Therefore, a decision support system which accommodates uncertainty has the potential to produce tighter, more efficient, and more robust taxiing schedules that bring an airport closer to its maximum capacity.

Some previous work has touched on this: Ravizza et al. (2014) explored a number of different modelling approaches, with the aim of reducing the error in estimated times. That paper found that, depending on the model, 3.2–5.7% of all flights were incorrectly estimated by over 3 min, with the lower end of that range (the best estimates) from a fuzzy rule based system. A common means of tackling this problem is adding time buffers to absorb uncertainty in the taxi times (Koeners and Rademaker, 2011). This paper presents a more sophisticated approach. The uncertainty in the taxi times is represented using fuzzy membership functions, which come directly from an adaptive Mamdani fuzzy model of the taxi times. The Quickest Path Problem with Time Windows (QPPTW) algorithm (Ravizza et al., 2013) is extended to use these fuzzy times, generating multiple routes for different levels of uncertainty. This allows the decision support system to find a route assignment that is robust in a range of situations, yet still uses a minimal time to complete the movement.

As far as we are aware, no other research has applied fuzzy systems to handling uncertainty in Ground Movement, though fuzzy approaches have been applied to handling uncertainty in other transportation problems (Yang et al., 2009; Huang et al., 2015) and are well established in more general scheduling problems (Fortemps, 1997; Lin, 2002; Petrovic and Song, 2006).

Thus, the major contributions of this paper are: an adaptive Mamdani fuzzy rule based system (FRBS) from Ravizza et al. (2014) is improved and extended to estimate taxi times and their uncertainties; and Fuzzy-QPPTW, an algorithm to allocate taxi routes to aircraft that are robust to taxi time uncertainty, is proposed. The new approach is demonstrated through the use of simulation to reduce delays caused by uncertainties in aircraft movements by 10–20% for higher levels of uncertainty. This has the potential to reduce fuel burned by stopping and starting aircraft, and make better use of congested taxiways at busy airports.

The rest of this paper is structured as follows. We begin in Section 2 with a review of existing work in airport Ground Movement and uncertainty. In Section 3 we fully define the problem, and then describe the FRBS and new algorithm Fuzzy-QPPTW in Section 4. In Sections 5 and 6 we detail our case study, centred around Manchester Airport, and the simulator used to compare the different algorithms. We present and discuss experimental results in Section 7 and finally in Section 8 we draw our conclusions.

2. Related work

2.1. Ground Movement

Airport Ground Movement is a difficult problem which has been the focus of extensive research over the past couple of decades. Comprehensive reviews of this area are (Atkin, 2013; Atkin et al., 2010).

Early work in this area (Gotteland and Durand, 2003; Gotteland et al., 2001; Pesic et al., 2001) used a list of routes that were either human-designed or generated before the algorithm was run using a shortest path algorithm. Heuristic search algorithms, such as genetic algorithms, selected an appropriate route and wait points for each aircraft. More recently, genetic algorithms were used to evolve the routes rather than choosing predefined ones (Jiang et al., 2013). Alternative efforts including (Yin et al., 2012; Clare and Richards, 2011; Guépet et al., 2016; Evertse and Visser, 2017; Samà et al., 2017) formulated Ground Movement as a mixed-integer linear programming problem. Ravizza et al. (2013) describe the QPPTW algorithm, an adaptation of Dijkstra's shortest path algorithm that accounts for the movements of previously-allocated aircraft. Rather than optimisation of routes, congestion on the airport surface has also been reduced by management of the speeds, time slots, landing runway, and pushback delay (Ma et al., 2016). Optimising gate allocations can also target reduced taxi times (Behrends and Usher, 2016). Often the focus is on optimising taxi times, but other objectives have attracted some attention, particularly reducing aircraft emissions and fuel consumption due to taxiing (Evertse and Visser, 2017; Chen et al., 2016a,b; Weiszer et al., 2015; Adacher et al., 2018). Integrated approaches to optimising Ground Movement with gate/stand allocation (Guclu and Cetek, 2017; Yu et al., 2017) and runway sequencing (Benlic et al., 2016; Guépet et al., 2017) have also been shown to provide more airport-wide improvements.

Most of the above methods assume fixed start or end times and taxi speeds. Some research has also attempted to account for the inherent uncertainty in this problem, which includes variations in push-back times, landing times and taxi speeds. Such uncertainty has been modelled as a fixed percentage of the initially defined taxi speed (Gotteland et al., 2001), with an aircraft occupying multiple positions on the taxiway graph simultaneously. An alternative is to use a planning horizon (Clare and Richards, 2011), so that aircraft routes were only determined up to a fixed time, and were then completed in subsequent iterations. Lesire (2010) used an increased temporal separation between aircraft to cope with uncertainty, and Koeners and Rademaker (2011) made use of time-margins around aircraft trajectories. The similar concept of buffering was discussed in Ravizza et al. (2013). Pfeil and Balakrishnan