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The importance of considering pushback time and arrivals when routing departures on the ground at airports☆

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Abstract

With the constant increase in air traffic, airports are facing capacity problems. Many airports are increasingly interested in utilising optimisation methods for specific airport processes. However, many such processes do happen in parallel, and maximising the potential benefits will require a complex optimisation model. A model which considers multiple processes simultaneously and the detailed complexities of the processes, rather than using more abstract models. This paper investigates how the arriving aircraft can affect the routing process and whether the pushback process can result into different types of delays. Furthermore, aircraft are routed backwards, starting from the destination in order to be at the runway on time and to respect the departure sequence. After testing our model with and without the arriving aircraft we found that arriving aircraft can indeed produce a lot of delays. Such delays would otherwise pass unnoticed as they result to departing aircraft choose different paths or pushback earlier so they be at the runway on time. Having an accurate model for the pushback process is important in order to understand in depth how the pushback process affects the other processes that happen in parallel. Furthermore, it led to more accurate and realistic model, which may assist the decision making process for ground movement operations and thereby help airports increase their capacity and become more environmentally friendly.

Introduction

Airports are getting increasingly busy and many are facing capacity problems. Furthermore, reducing CO_2 emissions is becoming an increasingly important consideration. Even though a considerable amount of optimisation research exists for various airport processes, few airports actually use automated optimisation processes, and those that do often use them only for a few processes. The ground movement of aircraft is one of the most important optimisation problems and includes a number of sub-problems that are beneficial to optimise (Atkin *et al*, 2010; Kjenstad *et al*, 2013). For example, departing aircraft will first push back from the gates (the pushback process), then taxi around the airports (the taxi process), and queue for the runway (runway sequencing process), whereas arrivals will land on a runway and need to taxi to the stands, potentially traversing taxiways in the opposite directions to the departing aircraft.

The various ground operations, such as: runway sequencing (Bennell *et al*, 2011; Apice *et al*, 2014), which can involve an explicit ground movement element (Atkin *et al*, 2007); gate allocation (Bouras *et al*, 2014; Neuman & Atkin, 2013); and ground movement routing and scheduling (Atkin *et al*, 2010, 2011), interact with each other and the solution of one can often affect another. Taking the interactions between these airport processes into consideration can lead to more accurate and realistic models, which can assist the decision making process for ground movement operations and help airports increase their capacity and become more environmentally friendly.

This paper focuses on the interaction between arriving and departing aircraft by using an integrated pushback process and respecting a fixed runway sequence. Our previous papers (Stergianos *et al*, 2015a, 2015b) introduced the explicit modelling of the pushback process into a ground movement model, and showed the importance of doing so by assessing the delays that were then identified by doing so, but would have otherwise been missed. However, that model still only considered departures, had only one entry point and exit point (i.e. used only one runway), and routed the departing aircraft in a pre-specified order, based on the time they had to push back. In this paper we show the results from new experiments using an even more realistic model. The improved model considers the effects of arriving aircraft, of differing aircraft

weight classes, of multiple runways, and of a more complex airport morphology. Real historic data is used for the experiments and the real runway sequence that was used is applied as a constraint. From this a better understanding of where, when, and why delays happen can be attained.

Problem description

An aircraft's push back process and the starting and warming up of its engines is a time consuming process. In a shared apron (the area of an airport where aircraft are parked) an aircraft's pushback process can delay other nearby aircraft (e.g. apron not be wide enough for two aircraft), and significant delays can occur when many aircraft wish to use the apron simultaneously. Furthermore, it might not be possible to start the pushback process if the apron area is already partly occupied. Some airlines do not even allow multiple aircraft moving in the same apron for safety reasons. For a busy airport, if not dealt with, these delays propagate and negatively affect the overall throughput of the airport.

Optimising the movements of aircraft can significantly reduce delays as well as minimise the time that an aircraft needs to have its engines running. Even a small reduction in the total time that an aircraft is moving on the ground can significantly reduce the fuel consumption and the carbon dioxide emissions for a busy airport. This will not only lead to reduced operation cost but could also increase the airport capacity.

Arriving aircraft are usually being prioritised as parking at the designated gate is a straightforward process and closing the engines as soon as possible will save fuel. Arriving aircraft are less affected by the delays as they do not need to respect any sequence or get involved with any time consuming process. However, having a higher priority can create delays for other aircraft. Departing aircraft on the other hand, have to be pushed back and then turn on and warm up their engines, which is a time consuming process that can cause delays (Stergianos *et al*, 2015a). Furthermore, the time that the aircraft have to push back has to be calculated based on the time that they have to reach the runway. An important factor to consider at airports is that the sequence of taking-off (the departure sequence) affects the runway throughput. For example, larger aircraft produce larger vortices and small aircraft are more affected by vortices. Being able to determine a good departure sequence in advance and then ensuring that it is respected can help to ensure a higher airport throughput. All of these needs must be taken into consideration.

One purpose of this paper is to investigate whether the pushback and routing process is affected by the arriving aircraft and if so, to what extent. It is important to quantify any benefits or drawbacks, such as increased delays, and have better insight into how different prioritisation of arriving aircraft can lead to larger or smaller delays.

Solution approach

In order to investigate whether the arriving aircraft affect the pushback process and cause additional delays, the model was executed with multiple configurations. First the arrivals were prioritised then the departures and each of these experiments were executed for arrivals alone, departures along and both. Both models make use of an improved version of the backwards Quickest Path Problem with Time Windows (QPPTW) which is a routing and scheduling algorithm. The algorithm was described in Atkin *et al* (2011) and is based an earlier algorithm described in Gawrilow *et al* (2008), which is an extension of Dijkstra's algorithm (Dijkstra, 1959). The algorithm considers time windows on the arcs and routes aircraft one at a time, with previous aircraft reducing the time windows which are available for subsequent aircraft. We refer the reader to Atkin *et al* (2011) for the full details and restrict the discussion in this paper to only the extensions.

Additions were made the algorithm in Stergianos *et al* (2015a), to include the pushback process in the routing process. This current paper uses the "backwards" version of the QPPTW algorithm and the pushback process is again incorporated into the algorithm. The "backwards" version of the algorithm routes the aircraft by using the time that an aircraft needs to be at the runway (the end of the journey) as an input instead of using the time that an aircraft departs from the gate. In this way it is possible to calculate the route and the latest departure time (from the gate) by taking into consideration all of the delays that may occur. This can reduce the waiting time at the runway by moving excess delay to the start of the journey, while parked at the stand, rather than in a queue at the runway.

The model is substantially improved in order to have a more realistic process compared the one we used in the previous paper. Zürich airport has been used for these experiments, presenting a more complex aircraft layout than Arlanda airport that we used before. Zürich airport has many taxiways making it possible for aircraft to use multiple routes to arrive at their destination. The importance of the morphology of the airport was highlighted in (Stergianos *et al*, 2015a, 2015b).

The change in layout and the use of real recorded data from Zürich enabled the algorithm to use multiple runways (entry and exit points) and for the calculation of a delay based on the specific runway that the aircraft is coming from or going to. Furthermore, there are now three different weight classes of aircraft considered. Aircraft, depending on their size/weight have different durations when pushing back. The multiple durations of pushbacks is also considered when calculating the delays that happen.

In order to be able to compare the delays that take place in various configurations, all of the component delays need to be calculated. The total delay for a day is the sum of all of delays that happen to all the aircraft on that day. Since it is not possible to observe an obvious delay when an aircraft chooses a longer path (there is no waiting time) the excess time is calculated by determining the minimum time that an aircraft needs to reach its destination and comparing this with the total routing time of that aircraft. The minimum time that an aircraft needs to reach its destination is calculated separately for each aircraft movement, by routing the flight in an empty graph with the use of a tailored version of Dijkstra's algorithm.

After determining the total routing time, the minimum routing time (m_f) and the pushback duration (p_f) it is easy to find the delay (i.e. excess travel time) for each flight. Equation 1 shows how the sum of all the delays that happen during a day are calculated using the notations defined in table 1.

$$Total\ delay = \sum_{f=1}^{n} (R_f - m_f - p_f) \tag{1}$$

Table 1. Table of definitions

Variable	*Explanation*
$f \in F := \{1, \dots, n\}$	A flight where F is the set of all flights and n is the total number of flights
R_f	The total routing time, as calculated by the algorithm for flight f
p_f	The pushback duration for flight f
m_f	The minimum time that it takes for an aircraft f to reach the runway from the gate (or vice versa)

Results

The model was executed using real data from Zürich airport, the largest airport of Switzerland (http://www.asap.cs.nott.ac.uk/external/atr/benchmarks/index.shtml, accessed 25 April 2016). Input information where: whether a flight was arriving or departing, the weight class (light, medium, or heavy), the starting point of the aircraft (the runway for arrivals, the gate for departures), the end point (the gate for arrivals, the runway for departures), the landing time for arrivals and the take-off time for departures. Real data for seven days was used for these experiments. The framework was programmed in Java and executed on a personal computer (Intel Xeon, 3.7GHz, 32GB RAM). The execution times varied from 9 to 15 seconds (prioritising arrivals) and 4 to 5 seconds (prioritising departures) total time for routing all moving aircraft in one day (from 780 to 840 aircraft movements), which is fast enough for real time routing, especially since far fewer aircraft would be simultaneously routed in practice. A weighted graph of Zürich airport was used for the routing of the aircraft. Since the QPPTW algorithm blocks the entire incoming edges of the node that an aircraft is heading to, additional nodes were added to long edges, splitting them into more reasonable distances (maximum edge weights). This avoided blocking edges for an unrealistically long time, providing a more accurate model of the interaction between aircraft. The routing process was performed sequentially by routing the arriving aircraft first (based on their landing time), routing the earliest arrival first, then sequentially routing the departing aircraft (based on the take-off time), starting from the latest departing aircraft and moving earlier in time. Sequencing them backwards in time like this was important for the departing aircraft in order to guarantee that aircraft would respect the correct sequence of arrival at the runway.

Table 2 shows the total delays that occur when the program routes different sets of aircraft. The first column shows the delays in seconds that occur when all the aircraft are routed, both arriving and departing. The information in parentheses shows the split of the delay between arriving (first number) and departing (second number) aircraft. The second column

shows the delays that occur when only the arriving aircraft are routed and column three when only the departing aircraft are routed. Column four shows the additional delay that is introduced to departures when the arriving aircraft are taken into consideration. Finally, the last column shows the number of additional individual delays that are introduced when arriving aircraft are also taken into consideration.

Table 2. Delays for different setups

	Total delays (arr/dep) [s]	*Arrival delays [s]*	*Departure delays [s]*	*Difference [s]*	*No. of additional delays*
Day 1	23904 (80/23824)	80	7814	16010	65
Day 2	20452 (63/20389)	63	4624	15765	72
Day 3	15646 (9/15637)	9	4888	10749	56
Day 4	25501 (74/25427)	74	9349	16078	77
Day 5	18427 (93/18334)	93	5436	12898	50
Day 6	22017 (29/21988)	29	8116	13872	58
Day 7	14906 (91/14815)	91	4905	9910	62

Firstly, a significant difference in the delay between arriving and departing aircraft is apparent. This is expected as the pushback process (which has been explicitly implemented) can cause both more delays and longer delays than those that happen when the aircraft are routed without modelling this process. Even though the airport has multiple runways there are many times when aircraft have to wait to push back or wait for another aircraft to push back and/or have to take a longer path. Arriving aircraft, on the other hand, do not have to wait for anything as they are prioritised so they can park as soon as possible after they land.

More importantly, by comparing the results of the two set ups, it is clear that most of the delays occur because of arriving aircraft. The departing aircraft need a clear apron to push back onto, and arriving aircraft disturb this process. The longest delays that happen are because departing aircraft cannot find a large enough window to push back in between other aircraft, whether arrivals or other departures. Even if one aircraft passes in front of a parked aircraft once every 4 minutes the parked aircraft simply cannot commit to initiating the pushback process. This results in departing aircraft pushing back much earlier than needed in order to ensure that they are going to arrive at the runway on time. In one extreme case there was an aircraft that had to start pushing back approximately 25 minutes before it would have done in isolation. With a 4 minute pushback duration and only 3 minute travel the distance, this is a considerable increase in time, and equates to a significant additional engine running time, wasting fuel. However, this is an unusual case. Most of the long delays are around 10 minutes.

The above results led to the belief that aircraft during the pushback process should have a higher priority. The experiments were re-executed giving priority to the departing aircraft. The results are summarised in Table 3.

Table 3. Different priorities in routing arrivals and departures

	Prioritise Arrivals (Arr/Dep)	*Prioritise Departures (Arr/Dep)*	*% Difference*
Day 1	23904 (80/23824)	11735 (7814/3921)	-51% (9668%/-84%)
Day 2	20452 (63/20389)	13222 (4624/8598)	-35% (7240%/-58%)
Day 3	15646 (9/15637)	8402 (4888/3514)	-46% (54211%/-78%)
Day 4	25501 (74/25427)	15260 (9563/5697)	-40% (12823%/-78%)
Day 5	18427 (93/18334)	10470 (5313/5157)	-43% (5613%/-72%)
Day 6	22017 (29/21988)	12132 (8116/4016)	-45% (27886%/-82%)
Day 7	14906 (91/14815)	8373 (4905/3468)	-44% (5290%/-77%)

It is clear from Table 3 that in all the cases, prioritising the departures results in a huge increase in delays for arrivals. However, the total delays are considerably lower, ranging from a 35% to a 51% decrease in each case. This is a significant difference, reducing the total delay to be closer to 3 hours rather than the 6 hours from just having different priorities. Part of the problem is that departures are limited in that they must use the apron near to their stand to push back onto, but this apron also forms a part of the route for other aircraft. Routing these aircraft first effectively reserves this apron for the pushback operation, potentially finding alternative routes around it for the other aircraft.

The above results show that arriving aircraft play a significant role in an airport. It is clear that the interaction of arrivals and departures can greatly increase the delay for whichever are routed second, so it is obviously important to consider both in the routing process. This shows that solving only half of the ground movement problem (either arrivals or departures) is unlikely to provide realistic estimates of delay at airports such as Zürich, where common taxiways are used. These results also indicate that it is better to prioritise the departures, due to the time that they spend in the pushback process, the need for that to be a continuous span of time in one location, and their inflexibility in where to spend this time.

Conclusions and future work

This paper has investigated the effects of the arriving aircraft in the routing and scheduling process of departing aircraft. Both the arriving and departing aircraft were routed with the QPPTW algorithm. Importantly, this algorithm routes aircraft one at a time from their starting to ending points, respecting the movements of other previously routed aircraft. The pushback process was explicitly implemented for departing aircraft, which were routed in reverse (backwards in time, from runway gate) to attempt to maximise the time at the gate before the engines are started.

The results showed that arriving aircraft had a large effect on the departure process. Having explicitly implemented a realistic pushback process resulted to large delays as pushbacks are a time consuming process (that is usually ignored) that greatly contributes to the total delay at an airport. Furthermore, by constraining the aircraft to arrive at the runway no later than a specific time, in a specific order magnified this effect resulting to even more delays.

Modelling various processes of an airport realistically by taking into consideration everything that happens before, during, and after the routing process is vital for understanding where and when delays can happen, and how and with what cost they can be avoided. This research has shown that the pushback process is particularly important in the effect that it has upon departures when there are arriving aircraft to deal with as well. In other words, when scheduling the ground movement, it is necessary to consider the departures and the time that they will spend blocking the apron while they start their engines. Furthermore, if the pushback process had not been explicitly modelled, the real-world problem of having to ensure sufficient gaps for these aircraft to push back into would not have been apparent. Similarly, without including the arrivals, the absence of such gaps for long periods of time would not have been clear. Importantly, this research considers both of these elements, simultaneously, resulting in a more accurate and realistic model of ground movement.

Future research will compare different types of airport layouts, making use of an airport layout generator. Different prioritisation methods will also be investigated. For this paper we considered only the QPPTW algorithm, which routes aircraft sequentially. We plan to investigate alternative methods too, as well as to investigate the potential for interleaving the routing of arrivals and departures, since it is important to understand the effects of various different routing methods on different morphologies of airports.

References

Apice, C., Nicola, C., Manzo, R., Mocci, V. (2014). Optimal scheduling for aircraft departures. Journal of Ambient Intelligence and Humanized Computing. Vol. 5, Issue 6, pp. 799-807.

Atkin, J.A.D., Burke, E.K., Greenwood, J.S., Reeson, D. (2007). Hybrid Metaheuristics to Aid Runway Scheduling at London Heathrow Airport. Transportation Science, Vol. 41, Issue 1, pp. 90-106.

Atkin, J.A.D., Burke, E.K., Ravizza, S. (2010). The airport ground movement problem: Past and current research and future directions. Proc. of the 4th Int'l Conf. on Research in Air Transportation (ICRAT), Budapest, Hungary.

Atkin, J.A.D., Burke, E.K., Ravizza, S. (2011). A more realistic approach for airport ground movement optimisation with stand holding. Proceedings of the 5th Multidisciplinary International Scheduling Conference (MISTA), Phoenix, AZ, USA, pp. 146-160.

Bennell, J.A, Mesgarpour, M., Potts, C.N. (2011). Airport runway scheduling. 4OR. Vol. 9, Issue 2 pp.115-138.

Bouras, A., Ghaleb, M. A., Suryahatmaja, U.S., Salem, A.M. (2014). The Airport Gate Assignment Problem: A Survey. The Scientific World Journal, vol. 2014, Article ID 923859.

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. Numerische Mathematik, Vol. 1, Issue 1, pp. 269-271.

Gawrilow, E., Kohler, E., Mohring, R., Stenzel, B. (2008). Dynamic routing of automated guided vehicles in real-time. Mathematics - Key Technology for the Future, pp. 165-178.

Kjenstad, D., Mannino, C., Nordlander, T., Schittekat, P., Smedsrud, M., (2013), Optimizing AMAN-SMAN-DMAN at Hamburg and Arlanda airport, Third SESAR INNOVATION DAYS (SID), Stockholm.

Neuman, U.M., Atkin, J.A.D. (2013). Airport Gate Assignment Considering Ground Movement. 4th Int'l Conf. on Computational Logistics, ICCL. Vol. 8197, pp. 184-198.

Stergianos, C., Atkin, J.A.D., Schittekat, P., Nordlander, T.E., Gerada, C., Morvan, H. (2015a). Pushback delays on the routing and scheduling problem of aircraft. 7th International Conference on Applied Operational Research, ICAOR. Lecture Notes in Management Science 7, pp. 34-40.

Stergianos, C., Atkin, J.A.D., Schittekat, P., Nordlander, T.E., Gerada, C., Morvan, H. (2015b). The effects of pushback delays on airport ground movement. Journal of Applied Operational Research, Vol. 7, No. 2, pp. 68-79.

University of Nottingham, Computer Science (2016) Air Transportation Research - Benchmarks, Retrieved from http://www.asap.cs.nott.ac.uk/external/atr/benchmarks/index.shtml [Accessed 25/04/2016].