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Pushback delays on the routing and scheduling problem of aircraft

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Abstract

With the constant increase in air traffic, airports are facing capacity problems. Optimisation methods for specific airport processes are starting to be increasingly utilised by many large airports. However many processes happen in parallel and a more complex optimisation model is required, which can consider multiple processes simultaneously. This paper focuses on the importance of the pushback process in the routing process. It investigates whether taking the pushback process into consideration can predict delays that otherwise would pass unnoticed. Having an accurate model for the pushback process is important for this and identifying all of the delays that may occur can lead to more accurate and realistic models that can be used in the decision making process for ground movement operations. After testing a model with a more detailed pushback process we found that a lot of the delays are not predicted if the process is not explicitly modelled. Having a more precise model with accurate movements of aircraft is highly important for an integrated model and will allow ground movement models to be used for more reliable integrated decision making systems on airports. Minimising these delays can help airports increase their capacity and become more environmentally friendly.

Introduction

Over the years, airports have become increasingly busy and many are already facing capacity problems. There is already a considerable amount of research into optimising the processes at the airports. Successful optimisation of these processes can save considerable fuel and emissions. The ground movement of aircraft is one of the most important operations and includes a number of sub-problems that can be optimised (Atkin *et al*. 2010). 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).

Ground operations can be divided into several categories, such as the runway sequencing problem (Bennell *et al*. 2011; Apice *et al*. 2014), which can involve an explicit ground movement element (Atkin *et al*. 2007), the gate allocation problem (Bouras *et al*. 2014; Neuman and Atkin, 2013) and the routing and scheduling problem itself (Atkin *et al*. 2010, 2011). These problems interact with each other and the solution of one can affect another. There has also been some research towards the integration of processes (Kjenstad *et al*. 2013). Taking the interactions between problems into account within models can increase the accuracy of the models, in terms of modelling the real world behaviour, as well as increasing the applicability of the results. This paper considers the integration of the pushback process into the ground movement problem. Although the ground movement problem has received significant research attention, there has been very little consideration of the pushback process. Tu *et al*. (2008) attempted to identify the delays that happen during the routing process with the use of statistical analysis. They took into consideration a number of trends and patterns like weather impact, delay built up from previous flights, seasonal and daily patterns, in order to predict the difference between the scheduled time and actual time that an aircraft was going to start the pushback process. Neuman and Atkin (2013) attempted to find the conflicts that may occur because of the pushback process or the conflicts that happen on aprons in order to better allocate aircraft to gates. Atkin *et al*. (2013) used a model to predict the delays at the stands or the runway in order to absorb this time at the stand, before the pushback process of the aircraft commences. Cheng (1998) developed a model that predicts and resolves conflicts on the apron taxiways in order to minimise the delay. However these models do not explicitly examine the effects of the pushback process, but instead focus on the minimisation of the total travel time.

In order to achieve a more realistic model that will be able to assess the effects of the pushback delays, the pushback process needs to be explicitly modelled within the routing process, taking into consideration the elements which are known to affect this delay and to ensure that the delay occurs by the stand, where pushback occurs, rather than being spread over the entire taxi duration. Here, the size of the aircraft and the morphology of the apron are two important aspects to consider, which influence the accuracy of the results. Accurate times as well as accurate sequencing of aircraft movements are key in an integrated model. This will allow models like this to be used not only for predictions but also for reliable integrated decision making systems at airports.

This paper presents our ongoing development of a more integrated and detailed model for the ground movement of aircraft. Section 2 describes the problem of the pushback process. Section 3 presents our solution approach. Section 4 states the results and Section 5 concludes the paper and proposes future work.

Problem description

The pushback process (which is the part of the ground movement process where the aircraft pushes back from the gate and starts its engines) is a crucial point where delays can (and do) happen. While an aircraft is being pushed back and its engines are started, it can block other aircraft that are moving around the airport. The pushback and engine start-up process is a time consuming process in many cases. While this is happening, other aircraft may not able to pushback if they are using stands that are close by. In cases where the apron is not wide enough to be used by two aircraft, a taxiway may be blocked by the aircraft for the duration of the process. In some cases airlines, for safety reasons, do not allow another aircraft to even move onto the same apron with an aircraft which is starting its engines, due to the size of and limited manoeuvrability within the aprons. Furthermore, aircraft are not able to start the pushback process if the area that they would push back to will not be free for the entire duration of the process. Figure 1 shows how delays can happen, illustrating how an aircraft pushing back would prevent another aircraft passing, or an aircraft passing could prevent a pushback.

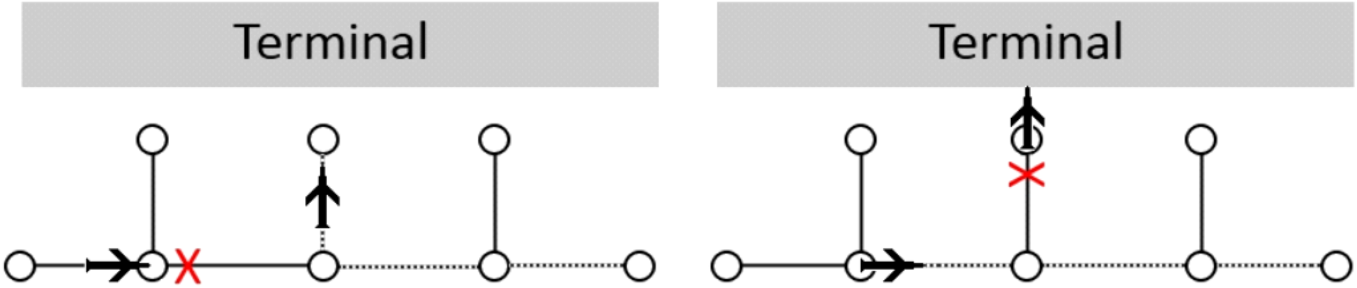

Fig. 1. Causes of pushback delays, delaying other aircraft or the aircraft pushing back

Pushback delays can cause significant delays at airports and add unpredictability to the predicted position of an aircraft at a given time. The absence of consideration of these factors in a model can lead to further delays later on down the path of an aircraft since the delay in the routing for one aircraft may have knock-on effects. For example, a take-off sequencing system would usually require knowledge of how early an aircraft can reach the runway, so delays will affect the feasibility of potential take-off sequences. An accurate model for scheduling and routing aircraft ground movement is important for providing any automated decision support to improve runway operations. Reducing waiting time at the runway by even a small percentage can save significant amounts of fuel, which directly influences the cost, as well as the carbon dioxide emissions. Reducing the delays and having improved ground movement can also increase the capacity of the airport.

The aim of this paper is to investigate and evaluate the effects upon the routes and schedules of explicitly taking into consideration the aircraft that are being pushed back. It is important to quantify any benefits, such as increased delay and this will be performed by comparing two models, one which takes into consideration the pushback process and one which does not.

Solution Approach

In order to investigate whether the pushback process is affecting the accuracy of the routing process two similar algorithms were used. Both of the algorithms implement the Quickest Path Problem with Time Windows (QPPTW) algorithm, a routing and scheduling algorithm, which was developed by Gawrilow *et al*. (2008) and later modified by Atkin *et al*. (2011) in order to be more suitable for airports. We refer the reader to Atkin *et al.* (2011) for full algorithm details and discuss only the extensions in this paper. The algorithm is an extension of Dijkstra's algorithm, which considers multiple aircraft in turn, rather than a single shortest path. As the path for the current aircraft is considered, all paths which were found for previous aircraft are taken into account, using time windows to block the graph edges for a specified time. A comparison of the two algorithms is now provided, for which the definitions of the variables are provided in Table 1.

Table 1. Table of definitions for Algorithms 1 and 2

Variable	*Explanation*
$f \in F := \{1, \ldots, n\}$	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
s_f	The time at which flight f should push back
w_e	The weight (necessary taxi time) of edge e
m_f	The minimum time that it takes for an aircraft f to reach the runway from the gate
d_f	Delay for aircraft f

Algorithm 1: this is a typical implementation of the QPPTW algorithm, as described in Atkin *et al.* (2011) and routes a number of aircraft without taking the blocking which can occur during the pushback process into consideration. In order to model the pushback delays, the algorithm delays the aircraft from setting off until the pushback duration has expired by delaying the start time of the operation. i.e. the start time for any aircraft f in **A**lgorithm 1 is given by $s_f + p_f$. The calculated total taxi time is given by Equation 1, since the routing time does not include the delay for pushback, so this needs to be added subsequently.

$$Total\ taxi\ time = \sum_{f=1}^{n} (R_f + p_f) \tag{1}$$

Algorithm 2: this is an extension of Algorithm 1, and includes the pushback duration at the start of the movement, moving the aircraft into the first node (where it would be located while it starts its engines) and then delaying it from commencing its journey until its pushback and engine start-up operation would have completed. For this duration it will be blocking the part of the apron into which it will push back, potentially delaying other aircraft. Algorithm 2 will start the routing process for aircraft f (which now includes the pushback process) at time s_f and the final total routing time will be determined by Equation 2, since the pushback delay has already been included in the routing time.

$$Total\ taxi\ time = \sum_{f=1}^{n} R_f \tag{2}$$

With Algorithm 2, the total routing time for an aircraft R_f will not only include the pushback duration for this aircraft p_f but will also include all of the delays that can be caused during the pushback process as well. These delays can be caused to an aircraft by its own pushback process (not being able to pushback immediately due to traffic) or the pushback process of other aircraft that are moving on the airport (where the pushback process of another aircraft blocks the path of this aircraft). Algorithm 2 requires an adaptation of the QPPTW algorithm. In order to have a more precise routing process, the pushback procedure was added to the QPPTW algorithm. Simply adding the pushback delay in the total taxiing time (as was done for Algorithm 1) cannot guarantee that there will not be any delays during the pushback process. In the extended algorithm (Algorithm 2), all of the edges that the aircraft checks for the first move have been modified to have an increased weight (where the weight of an edge is the travel time to traverse that edge), the new weight being the normal weight of the edge plus the pushback duration. Figure 2 shows an aircraft f_1 that is pushing back from node A to node B. The new weight of the edge AB is $w'_{AB} = w_{AB} + p_f$. The pushback duration p_f is determined by the size of the aircraft f.

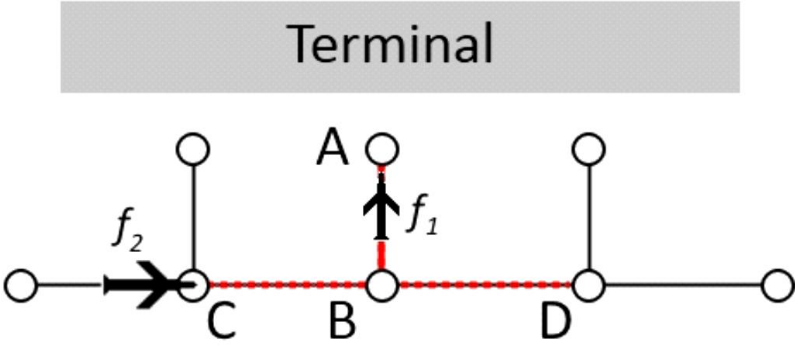

Fig. 2. Blocked edges during pushback

The QPPTW algorithm finds the shortest path, taking into consideration the added delay. All of the edges that are connected to the first edge are blocked, preventing other aircraft from coming too close to the aircraft which is pushing back. In the example in Figure 2, this means that all of the edges AB, BC, BD are blocked for the entire duration on the pushback process (w'_{AB}). Blocking the edges ensures that the aircraft will reach its destination in the shortest amount of time allowing for the fact that edges can be used by a maximum of one aircraft at a time. Figure 2 also illustrates the situation where there is another aircraft f_2 that has to wait for aircraft f_1 to finish the pushback process. Aircraft such as f_2 that get blocked have to either wait or choose a longer path, if there is one.

Comparison of algorithms: in order to be able to compare these two algorithms, an effective way to calculate the delays is needed. In order to make sure that all delays are found, even the ones that are caused by taking longer paths, the minimum routing times are calculated for all gates. Dijkstra's algorithm is sufficient for this, so the QPPTW algorithm is executed for each of the gates (twice, once for arrivals and once for departures), on an empty airport without the enhancements which block edges and readjust the time windows. Once the minimum times have been found (the quickest path, without any delay) it is easy to establish the exact additional delay that each aircraft has, regardless of whether this delay is due to waiting for other aircraft to move, or increased taxi time due to taking a longer path, re-routing around any blocks (e.g. pushback blocks), on the optimal path. Given the preceding calculations and definitions, the delay for each aircraft is calculated using Equation 3, and the total delay is merely the sum of all delays for individual aircraft.

$$d_f = R_f - m_f \tag{3}$$

Results

Both algorithms were executed using data for a typical morning at Stockholm's Arlanda airport, the largest airport in Sweden (http://www.asap.cs.nott.ac.uk/external/atr/benchmarks/index.shtml, accessed 21 April 2015). For this experiment 54 aircraft were routed and the results are shown in Tables 2 and 3. The framework was programed in Java and was executed on a personal computer (Intel Core i3, 2.5GHz, 4GB RAM). The execution time for both algorithms is around 1 second which is fast enough for real time routing. For these experiments a weighted graph of Arlanda airport was used. Since the QPPTW algorithm that was used for the core of the routing process works by blocking edges, the maximum distance between two nodes was limited by inserting nodes into long arcs, at spacing of approximately 80 meters, simulating the effects of being able to have multiple aircraft queue one behind another along the taxiway. The routing process of the aircraft was done sequentially starting from the aircraft with the earliest start time.

Table 1. Total delays and total taxi time for each algorithm

	Total delays [s]	*Total taxi time [s]*
Algorithm 1	77	26780
Algorithm 2	1300	28003
Difference	1223	1223

Table 2. Flights which are affected by ground movement delays

Flight no	*Start time*	*Stand*	*Routing time Alg1*	*Routing time Alg2*	*Delays Alg1*	*Delays Alg2*	*Time dif.*
2	05:05:17	F39R	590	762	0	172	172
5	05:15:22	S78	307	473	0	166	166
8	05:25:26	57	408	582	0	174	174
10	05:29:46	G142	696	881	0	185	185
12	05:34:05	F37	608	632	12	36	24
17	05:45:36	11	514	514	19	19	-
25	05:58:34	41	444	444	9	9	-
28	06:04:19	40	486	486	19	19	-
31	06:10:05	42	462	471	0	9	9
36	06:15:50	38	479	479	5	5	-
39	06:21:36	34	483	564	0	81	81
41	06:27:22	39	440	614	0	174	174
44	06:30:14	33	470	708	13	251	238
Total			26780	28003	77	1300	1223

Table 2 shows the total delay and total taxi time for the 54 routed aircraft. The first two rows show the times that are produced after running Algorithm 1 and 2 respectively while row three shows the time difference between these times. Table 3 shows the total routing time and the total delay for each aircraft. Comparing the two algorithms, we can see that Algorithm 2 has considerably more delays. Out of the 54 aircraft, 13 are delayed when routed with Algorithm 2 but have smaller or no delays when routed with Algorithm 1. The additional delay is more than 1 and a half minutes per flight on average (94 seconds). The sum of detected delays when routed using Algorithm 2 is 21 minutes and 40 seconds (1300 seconds) whereas the sum of the delays when using Algorithm 1 is only 1 minute and 17 seconds. Overall, Algorithm 2 has detected 9 more cases that cause delays than Algorithm 1, for a total of 20 minutes and 23 seconds additional time of delay.

Both of the causes for delays were observed in the experiments, when an aircraft pushes back and blocks the apron for another aircraft (i.e. the aircraft pushing back is doing the blocking) and when an aircraft needs to push back, but is unable to do so because the apron is already being used (even for a short period of time) by another aircraft (i.e. the aircraft pushing back is being blocked). In most cases where aircraft delay each other, the delay was experienced by the aircraft that was set to pushback later. This aircraft will often not be able to start the pushback process at all since the edges in front of the stand would need to be clear for the whole duration of the pushback process, but the other aircraft blocks them for part of the duration. In some cases, one aircraft which was pushing back delayed another aircraft which wanted to pass that position, or forced it to take a longer route. For example, in the case of aircraft 9, which is a heavy aircraft, it takes 432 seconds to push back and turn its engines on. Aircraft 10 starts pushing back at the same time, but finishes its pushback process faster since it is a medium aircraft (240 seconds). It then has to wait for aircraft 9 for 166 seconds. The remaining 19 seconds of the delay for aircraft 10 are due to delays that occur in the rest of the path. This is an obvious example of the blocking during pushback causing a considerable proportion of the additional delay which is incurred during the routing and scheduling process.

Overall, the majority of the additional delay was experienced on the aprons and was caused directly by the pushback process. However, in some cases there is also a different composition of the overall delay of an aircraft. Due to changes in the movements of an aircraft (caused by other aircraft that push back) other delays can occur later on as the aircraft can fall behind another aircraft if it delays clearing the apron on time. This happens with aircraft 9 – 10 – 12 where aircraft 9 delays aircraft 10 and then aircraft 12 and 10 interact. This can have a great effect on the sequence in which aircraft arrive at the runway as well. For example, with Algorithm 1 the sequence in which aircraft arrive at the runway is 10 – 11 – 9 – 12, whereas with Algorithm 2 it is 11 – 9 – 10 – 12. Without the pushback process model, aircraft 10 is not delayed by aircraft 9 at all. This results in aircraft 10 not only moving in front of 9 but also avoiding a conflict with aircraft 11. Having no conflicts along its path, aircraft 10 arrives at the runway before both aircraft 11 and 9. This can potentially cause even more delays since the take-off process may then be affected by the sequence in which the aircraft arrive, which can affect the throughput since the size of an aircraft influences the strength of the wake vortex behind the aircraft, which in turns influences the time that the next aircraft can take-off (Atkin *et al*. 2007).

In summary, a poor allocation of flights on gates has contributed to producing a large increase in delays (21 minutes and 40 seconds) within just two hours. However, since a medium aircraft can delay another aircraft up to 4 minutes during the pushback process alone, it is not unlikely to have this amount of delay on airports when aircraft that start at the same time are allocated to stands which are close together. The above results verify that the pushback process can affect the movement of aircraft, causing many delays that can have long durations.

Conclusion

This paper has investigated the importance of the pushback process in the routing and scheduling problem of the ground movement of aircraft. Two similar algorithms were used to examine the effect of the pushback process. One that takes into consideration the pushback process and one that doesn't. In both cases the ground movement problem is solved using the QPPTW algorithm, which finds the quickest path that an aircraft can take in order to go from point A to point B, taking into consideration the movement of previously routed aircraft. In the second algorithm the pushback procedure is implemented within the aforementioned algorithm to have a more realistic overall result. The final program that uses the improved algorithm is able to route and schedule aircraft taking into consideration the pushback/turning-engines-on procedure. Furthermore, other aircraft that are being routed take the pushback processes of previously routed aircraft into consideration as well.

Flight data for part of a day was used as an input. Having the start time and gate for each aircraft made it possible to examine the interactions between aircraft, especially around the gates and aprons where aircraft start the routing process. The experimental results showed that aircraft which were pushing back were both delaying and being delayed by other aircraft. Additional delays could also occur further down an aircraft's path as well, due to the change in the time that it leaves the apron. Furthermore, the sequence of aircraft that arrive on the runway can be affected since pushback delays can hold an aircraft for a significant amount of time. The experimental results show that the pushback process can contribute a considerable amount of delay. In order to optimize the whole ground movement process it is vital to have a detailed model of the airport aprons and the pushback process of the aircraft. The extended algorithm provides a better approach that identifies delays that happen due to the pushback process. Not only is the pushback duration itself included, but the consequences of the interaction between aircraft are also considered, which can cause further delays for both the aircraft which is pushing back and other aircraft at the airport. Accurately modelling the positions of these delays (i.e. at the stands rather than distributed over the taxi process) has been important for properly understanding the effects of the delays.

Future research will investigate the delays that are caused by allocating flights which are on stands that are close together as well as considering different airport layouts, different types of gates, and a better mix of aircraft types and sizes. We will also consider integrating the extended routing process into other operations that occur in parallel at an airport, such as the gate allocation process and the runway sequencing process.

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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. Proceedings of the 4th International Conference 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.

Atkin, J.A.D., De Maere, G., Burke, E.K., Greenwood, J.S. (2013). Addressing the Pushback Time Allocation Problem at Heathrow Airport. Transportation Science, Vol. 47, Issue 4, pp. 584-602.

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.

Cheng, Y. (1998). Solving Push-Out Conflicts in Apron Taxiways of Airports by a Network-Based Simulation. Computers & Industrial Engineering. Vol. 34, No. 2, pp. 351–369.

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., Schittekat, P., Smedsrud, M. (2013). Integrated surface and departure management at airports by optimization. 5th International Conference on Modelling, Simulation and Applied Optimization (ICMSAO), pp. 1–5.

Neuman, U.M., Atkin, J.A.D. (2013). Airport Gate Assignment Considering Ground Movement. 4th International Conference on Computational Logistics, ICCL. Volume 8197, pp. 184–198.

Tu, Y., Ball, M.O., Jank, W.S. (2008). Estimating Flight Departure Delay Distributions – A Statistical Approach with Long-Term Trend and Short-Term Pattern. Journal of the American Statistical Association, Volume 103, Issue 481, pp. 112–125.

University of Nottingham, Computer Science (2015) Air Transportation Research - Benchmarks, http://www.asap.cs.nott.ac.uk/external/atr/benchmarks/index.shtml, Accessed 21/04/2015.