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A heuristic approach to greener airport ground movement

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***Abstract*— Ever increasing air traffic, rising costs and tighter environmental targets create a pressure for efficient airport ground movement. Ground movement links other airport operations such as departure sequencing, arrival sequencing and gate/stand allocation and its operation can affect each of these. Previously, reducing taxi time was considered the main objective of the ground movement problem. However, this may conflict with efforts of airlines to minimise their fuel consumption as shorter taxi time may require higher speed and acceleration during taxiing. Therefore, in this paper a multi-objective multi-component optimisation problem is formulated which combines two components: scheduling and routing of aircraft and speed profile optimisation. To solve this problem an integrated solution method is adopted to more accurately investigate the trade-off between the total taxi time and fuel consumption. The new heuristic which is proposed here uses observations about the characteristics of the optimised speed profiles in order to greatly improve the speed of the graph-based routing and scheduling algorithm. Current results, using real airport data, confirm that this approach can find better solutions faster, making it very promising for application within on-line applications.**

I. Introduction

THE airport ground movement problem plays a central role among the ground operations as it links runway sequencing and the gate or stand allocation problem [1]. The main goal of the ground movement problem is to find routes and schedules for all aircraft moving on the airport surface in an effective manner. With increasing air traffic, airports are likely to become bottlenecks, creating pressure for more efficient ground movement operations with the aim of reducing taxi times. On the other hand, efforts of airlines to reduce costs together with increasingly tighter environmental regulations result in a demand to cut fuel consumption. However, this goal can be in conflict with minimising the total taxi time, as shorter times normally require higher taxiing speeds and accelerations.

Previous research on ground movement almost exclusively considered the taxi time objective as the most important for the ground movement problem. Minimisation of the total taxi time is the main goal of the genetic algorithm used by Pesic et al. [2], the mixed integer linear programming approach proposed in [3], [4], and the graph-based algorithms in [5], [6]. Apart from the total taxi time as an objective, deviations from the scheduled time of departure or arrival are also considered within a multi-objective optimisation framework by Balakrishnan and Jung [7], Deau et al. [8], Smeltink et al. [9], and Gotteland et al. [10]. Similarly, a weighted sum of objectives including the total taxi time, the delays for arrivals and departures, the number of arrivals and take-offs, the worst routing time and the number of controller interventions is minimised in the research by Marín and Codina [11]. The paper by Garcia et al. [12] uses another time related objective: the makespan, i.e. the duration from the first to the last aircraft movement.

Work considering the stand holding problem [13], [14], [15] indirectly takes the fuel consumption into account, and tries to maximise the time that aircraft spend at the stand, with their engines off, rather than taxiing. The main assumption is that a shorter taxi time will result in lower fuel burn.

The only paper we are aware of that simultaneously considers taxi time as well as fuel consumption is the recently published work by Ravizza et at. [16]. That approach combines a routing and scheduling algorithm [5] with the Population Adaptive based Immune Algorithm (PAIA) [17] in search of the trade-off between the total taxi time and fuel consumption. The problem with this approach lies in its high computational demand and also the adoption of a fuel consumption index rather than actual fuel burn. However, the results reported in that paper indicate that time and fuel consumption can be conflicting objectives depending on the specifics of an aircraft.

In this paper, we further investigate mechanisms to speed up the approach in [16], so that the proposed combined approach can be adopted for on-line application of airport management systems. Furthermore, this has to be done without degrading the search for the trade-off between the total taxi time and fuel consumption. To this aim, a new heuristic which uses observations about the characteristics of the optimised speed profiles is proposed for finding different speed profiles for the considered aircraft. The ICAO database [18] is utilized in order to calculate fuel consumption.

The rest of the paper is organized as follows: Section II provides a description of the multi-component optimisation problem and the related routing, scheduling and speed profile optimisation subproblems. The combined solution method is introduced in Section III. The proposed approach is tested using a dataset provided by Zurich Airport, and preliminary results are shown in Section IV. Finally, conclusions are drawn in Section V.

II. Problem description

The optimisation problem presented in this paper is a multi-component optimisation problem. Multi-component

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optimisation problems consist of two or more optimisation problems which are:

- *combined* - the solution of the main problem requires the solution of several subproblems,
- *interdependent* - the solution for one subproblem affects the solution for the other subproblem.

Examples of other multi-component optimisation problems include the travelling thief problem [19], the vehicle routing problem under loading constraints [20], and the combined runway sequencing and routing problem [21].

The ground movement optimisation problem considered in this paper consists of two subproblems, namely the routing and scheduling problem and the speed profile optimisation problem, where the following two objective functions are to be minimised:

- g_1: total taxi time,
- g_2: fuel consumption.

This multi-component ground movement optimisation problem combines two problems which are difficult to solve on their own, but are even more so together, due to the interdependence between them. The solution of the speed profile optimisation problem will affect the solution of the routing and scheduling problem and vice versa. In the following, Section II-A explains the first subpı
Section II-B describes the second subproblem.

A. Routing and scheduling problem

The aim of the routing and scheduling problen
aircraft from source to destination locations in
fuel efficient manner, respecting routes of other ai
preventing conflicts between them. The airpor
represented as a directed graph, where the edg
the taxiways and the vertices represent the taxiwa
intermediate points and sources/destinations suc
stands and runway exit points (see Fig. 1).
considered to occupy edges and only one aircra
along one edge at a time so that a minimum saf
from all other aircraft is ensured.

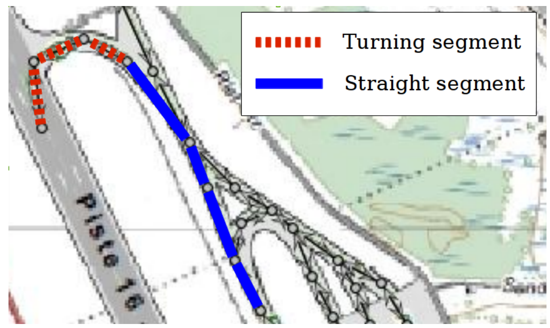
For the single-objective version of this proble
et al. [5] developed a sequential routing and
algorithm, the Quickest Path Problem with Tin
(QPPTW), which has the total taxi time as its mai
The algorithm routes aircraft one after another in
according to their pushback/landing time respe
ously reserved taxiways of other aircraft. Alrea
routes do not change whenever a new aircraft i
consideration. In order to consider another objec
QPPTW algorithm proposed in [16] is employed i
This algorithm generates not only the best route (
minimum taxi time) but a set of the k-best solu

The information about the speed of aircraft
vidual edges is extremely important for the a
it determines when aircraft will pass over the
optimal speed profile of each aircraft is disc
Therefore, the two subproblems are interconnect
of a multi-component optimisation problem, wh

the scheduling problem for a new aircraft is only possible after finding a solution to the speed profile optimisation problem of the previously routed aircraft.

B. Speed profile optimisation problem

The second optimisation subproblem focuses on finding a set of Pareto optimal ground movement speed profiles for a given route, with the aim of minimising fuel consumption and taxiing time simultaneously. The route of the aircraft consists of segments where one segment can contain several edges and, for example, several consecutive straight edges typically represent one straight segment (see Fig. 1).



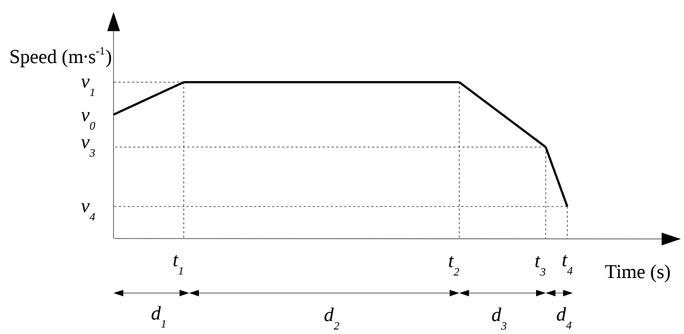


Fig. 2. An example of a speed profile with four phases.

phase in which an aircraft maintains a constant acceleration rate a_1 over the distance d_1, thus increasing its speed from the initial speed v_0 at the start of the segment to v_1. During the second phase, an aircraft will traverse at the constant speed v_1 until the end of the second phase d_2 is reached. In the third and the fourth phase, an aircraft will decelerate from the speed v_1 to the speed v_4 at the end of the segment. The last two phases have different deceleration rates where, a_4 is equal to the maximum deceleration rate which enables the speed to be quickly reduced to v_4. As for the third phase, the deceleration rate a_3 will be uniquely determined by a_4 and

d_4, since v_3 can be derived backwards given a_4, v_4, d_4 and the length of the third phase is equal to $d_3 = d - d_1 - d_2 - d_4$.

For turning segments we assume that the aircraft will have a constant speed v_{turn}. The maximum speed on straight taxiways $v_{straight}$ is restricted to 30 knots (15.43 m·s^{-1}) and turning speed v_{turn} is set to 10 knots (5.14 m·s^{-1}). The consecutive segments are linked together so that the final speed v_4 of the preceding segment is the initial speed v_0 of the subsequent segment. Furthermore, the maximum acceleration and deceleration rate a_{max} is set to 0.98 m·s^{-2} for passenger comfort.

As a result there are four free variables a_1, d_1, d_2, d_4 which define a unique speed profile over a segment. By searching for values of these four variables, one can explore different speed profiles with different taxi time and fuel consumption. The taxi time needed to traverse a single segment (objective g_1) is the sum of the time t_j spent in the different phases (acceleration, travelling at constant speed, braking and rapid braking):

$$g_1 = \sum_{j=1}^{4} t_j \tag{1}$$

The calculation of the fuel consumption for a given speed profile is discussed in the next section.

C. Fuel consumption during ground movement

In recent years, several researchers have investigated the fuel consumption of an aircraft during ground movement. Data from the International Civil Aviation Organization (ICAO) engine emissions database [18] is commonly used as a reference. The database states thrust levels η for different operational situations (idle, take-off climb, approach) as a percentage of full rated power of the engine F_o with corresponding fuel flow f per second, where 7% of full rated power is assumed for idle and ground taxiing. However, several studies [22], [23], [24] argued that the thrust level was lower during taxiing. Morris [22] found that values of 5% to 6% are more realistic for most aircraft.

Nikoleris et al. [24] assumed the thrust level η to be 4% for idle, 5% for brake and taxiing at constant speed, 7% for turning and 9% for breakaway. The fuel consumption in their paper is then calculated by multiplication of the time spent in each state with the corresponding fuel flow f. Fuel flows for each state are obtained by linear interpolation using the fuel flows reported in ICAO database at 7% and 30% engine thrust levels.

Khadilkar and Balakrishnan [23] presented a linear function with parameters estimated by regression from actual data captured by flight data recorders. Their research showed that the total taxi time along with the number of acceleration events is the main factor contributing to fuel burn.

Finally, Chen and Stewart [17] presented a physics based model to estimate the fuel consumption index as a value directly related to fuel burn.

This study combines the approach of Chen and Stewart [17] for obtaining the thrust level during taxiing and fuel flow estimation similar to [24]. As mentioned in Section II-B, four phases are defined for a straight segment: acceleration, constant speed, braking and rapid braking. Constant speed is assumed for turning segments. For the phase of braking, rapid braking or turning the assumed thrust levels are given in Table I.

TABLE I

BASELINE ASSUMPTIONS FOR THRUST LEVELS DURING TAXIING.

Baseline assumptions	Thrust level η of full rated power
Brake and rapid brake thrust	5%
Thrust during turning	7%

For other phases, the thrust levels are estimated as follows. Firstly, the thrust is calculated using the rolling resistance F_r of the aircraft, its weight m and acceleration a:

$$Thr = F_r + m \cdot a \tag{2}$$

The rolling resistance F_r is proportional to the rolling resistance coefficient μ and normal force $m \cdot g$, where g =9.81 m·s^{-2}:

$$F_r = \mu \cdot m \cdot g \tag{3}$$

In this work, the rolling resistance coefficient μ represents the coefficient for concrete surface and is set to 0.015. Then, the thrust level η is calculated as a ratio of calculated thrust Thr and maximum power output F_o of the engine:

$$\eta = \frac{Thr}{F_o} \tag{4}$$

The fuel flow f corresponding to the thrust level η is obtained by linear interpolation/extrapolation using reported fuel flows from ICAO database at 7% and 30% similarly as in [24]. Finally, the fuel consumption for the segment (objective g_2) is calculated by multiplication of fuel flow f_j for the specific phase j and the time t_j spent in this state:

$$g_2 = \sum_{j=1}^{4} f_j \cdot t_j \tag{5}$$

III. COMBINED SOLUTION METHOD

A. Integrated procedure

This section provides a detailed description of the integrated procedure for solving the routing and scheduling problem and the speed profile optimisation problem. The integrated procedure uses the same approach (see Fig. 3) as presented in [16] which approximates the Pareto front by generating ℓ points on the Pareto front. In each iteration (lines 3–11) the whole set of aircraft is scheduled using the k-QPPTW algorithm and one point of the Pareto front is generated. As the parameter i incrementally increases (line 2) the algorithm finds points on the Pareto front gradually changing from the most time-efficient solution to the most fuel-efficient solution.

The aircraft are considered sequentially according to their pushback/landing time (line 1). For each aircraft a, the k-best routes are generated based on their taxi times, assuming

```
1:  Sort aircraft by their pushback/landing time;
2:  for i = 1 to ℓ do
3:    for all aircraft a do
4:      Generate the shortest k routes using the k-QPPTW
        algorithm;
5:      for route k of aircraft a do
6:        Approximate the Pareto front of both objectives
          using the heuristic;
7:      end for
8:      Generate the combined Pareto-front for the source-
        destination pair of aircraft a;
9:      Discretise this Pareto front into ℓ roughly equally
        spaced solutions;
10:     Select the i-th solution and reserve the relevant
        route for aircraft a;
11:   end for
12:   Save the accumulated values for all aircraft for both
      objective functions for the global Pareto front;
13: end for
```

Fig. 3. Integrated procedure for trade-off analysis.

constant speed $v_{straight}$ and v_{turn} for straight and turning edges, respectively (line 4). Then, for each route, different speed profiles are explored using a heuristic presented in Section III-B to approximate the Pareto front taking into consideration all reservations that were made by previously scheduled aircraft (lines 5–7). The subroutine in line 8 combines the different Pareto fronts for k routes and by selecting non-dominated solutions it produces the global Pareto front for the given source-destination pair of aircraft a. The resulting Pareto front is discretised into ℓ roughly equally spaced solutions (line 9). The i-th solution on the Pareto front is selected in line 10 and that route, together with the corresponding speed profile, is used to schedule aircraft a.

The inner loop (lines 3–11) is repeated until all of the aircraft from the dataset have been routed and the total taxi time and the total fuel consumption is accumulated to generate a single solution on the global Pareto front (line 12).

B. Heuristic for speed profile optimisation

In order to quickly approximate the trade-off curve between the total taxi time and fuel consumption on a given route, a heuristic procedure is devised. This heuristic is based on the following observations which were noted during the initial experiments with using PAIA as a solution method for the speed profile optimisation problem:

1) Aircraft only accelerate with the maximum acceleration $a_{max} = 0.98$ m·s^{-2} in order to minimise the acceleration time.
2) Fuel consumption during braking is comparable with the fuel burn during constant speed.

The first observation is supported by a close investigation of Eq. 2 which reveals that acceleration is linearly penalized. On the other hand, the acceleration time decreases in a non-linear manner with increasing acceleration rate. When time and fuel flow corresponding to thrust is multiplied in Eq. 5 the resulting function is convex. This is illustrated in Fig. 4, which shows a situation when an Airbus A320 accelerates from v_0= 0 to v_{max}= 15.43 m·s^{-1}. Different acceleration rates result in different fuel consumption and time. As is clear from the figure, the maximum acceleration rate has the shortest time and the lowest fuel consumption at the same time. The goal of the optimisation is to minimise the time and fuel cost simultaneously, therefore, in order to do so the maximum acceleration rate $a_{max} = 0.98$ m·s^{-2} is favourable to use. However, this conclusion holds only if no time constraints from the previously routed aircraft are imposed on the edges, hence, making this approach a heuristic. If some edges have time constraints in place, using the maximum acceleration rate can be infeasible.

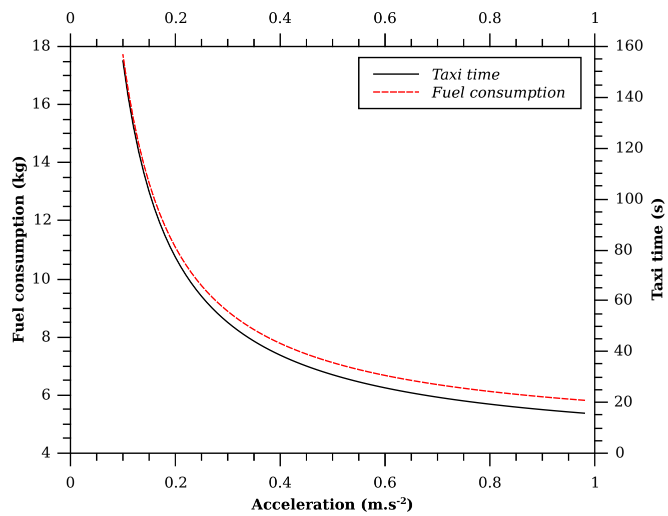


Fig. 4. The maximum acceleration rate has the shortest time and the lowest fuel consumption at the same time. Example of an Airbus A320 accelerating from v_0= 0 to v_{max}= 15.43 m·s^{-1}.

The second observation is supported by similar fuel costs for maintaining a constant speed for an aircraft as for braking. The thrust level for braking is assumed to be 5% (see Table I). During constant speed, the thrust is equal to the rolling resistance. The thrust level is then a ratio of the rolling resistance and full rated power of the engines. The thrust level for maintaining a constant speed is 3.9%, 5.1%, 5.9%, respectively for Learjet 35A, Airbus A320 and Airbus A333 aircraft. As a result, travelling at constant speed is preferred to braking (therefore, $d_3 = 0$) as it minimises time at no or little extra cost.

These observations then lead to a constrained search space, where some of the original decision variables a_1, d_1, d_2, d_4 can be determined beforehand. The first observation implies that the decision variable a_1 is fixed to 0.98 m·s^{-2}. The second observation will maximize the distance d_2 during which the aircraft travels at constant speed v_{max}, since braking will not save fuel, but will increase traversing time. With maximized d_2 the rapid braking distance d_4 using deceleration a_{max} = 0.98 m·s^{-2} to slow down from v_{max} to v_4 can be easily calculated using the following equation:

$$d_4 = \frac{v_{max}^2 - v_4^2}{2a_{max}} \tag{6}$$

The only decision variable left undecided is the acceleration distance d_1 which affects the maximum speed v_{max} that can be achieved over the segment. The maximum speed v_{max} affects the fuel consumption as well as the time needed to traverse the segment. The resulting functions for time and fuel consumption are shown in Fig. 5 for segments of different length D for an Airbus A320. As can be seen from the figure, fixing v_{max} determines the taxi time and fuel consumption for the segment. Then, the remaining task is to search for the optimal values of v_{max} and hence d_1.

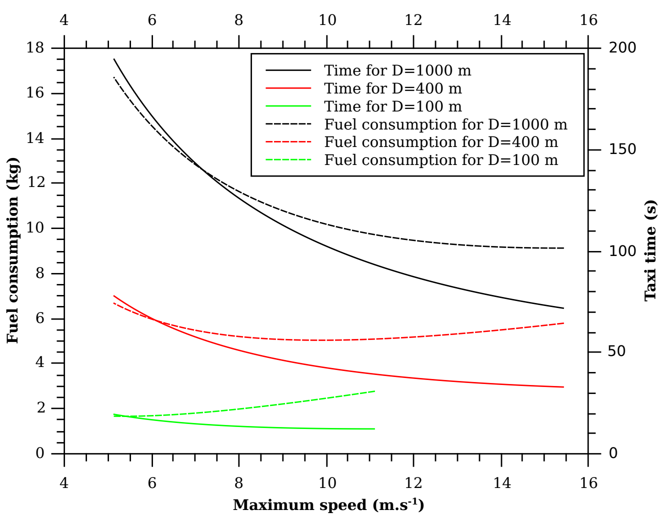


Fig. 5. Trade-off between taxi time and fuel consumption for different maximum speed that can be achieved over the segment of length D for an Airbus A320.

The search for a trade-off is performed as described by Fig. 6. The heuristic starts by iteratively generating speed profiles for each segment seg_n of the route with the maximum speed v_{max} set to a value from v_{max} = 5.14 m·s^{-1} (10 knots) to v_{max} = 15.43 m·s^{-1} (30 knots), with a step of 1 m·s^{-1}. In total, $p = 12$ solutions are generated for each segment.

In order to construct the Pareto front for the whole route, the subroutine (lines 8–18) iteratively selects weights for $p = 12$ iterations in total. For each segment seg_n, the solutions generated in line 4 are ranked according to utility obtained by a linear combination of weighted taxi time (objective g_1) and fuel consumption (objective g_2). The solution with the best (i.e. minimum) utility is selected for the segment seg_n. The resulting complete solution for the whole route and one combination of weights w_1, w_2 is constructed as a set of best selected speed profiles for all segments (line 13). Finally, the solution is checked for potential violations

1: **for all** seg_n in route **do**
2: $\quad p = 0$;
3: $\quad$ **for** $m = v_{turn}$ **to** $v_{straight}$ **step** 1 m·s^{-1} **do**
4: $\quad\quad$ generate speed profile with $v_{max} = m$;
5: $\quad\quad p = p + 1$;
6: $\quad$ **end for**
7: **end for**
8: **for** weight w_1 = 0 **to** 1 **step** $\frac{1}{p}$ **do**
9: $\quad w_2 = 1 - w_1$;
10: $\quad$ **for all** seg_n in route **do**
11: $\quad\quad$ assign utility $w_1 \cdot g_1 + w_2 \cdot g_2$ to every speed profile generated in line 4;
12: $\quad\quad$ select speed profile with the minimum utility;
13: $\quad\quad$ assign parameters a_1, d_1, d_2, d_4 to complete solution for the whole route;
14: $\quad$ **end for**
15: $\quad$ **if** complete solution violates time windows of already routed aircraft **then**
16: $\quad\quad$ discard solution;
17: $\quad$ **end if**
18: **end for**
19: **if** no feasible solutions exist **then**
20: $\quad$ add buffer time;
21: $\quad$ shift time windows and **goto** line 1;
22: **end if**
23: **return** set of solutions approximating the Pareto front;

Fig. 6. Heuristic for speed profile optimisation.

of time windows of already routed aircraft. Non-feasible solutions are discarded.

If all of the solutions generated by the subroutine in lines 8–18 have been discarded due to time window violations then a buffer time is added in line 20 to this aircraft's push-back/landing time until it is possible to taxi unimpededly. The time windows of the other aircraft are updated accordingly and the search is restarted (line 21).

IV. Experimental Results

A. Description of the problem instance

The algorithm was tested on a dataset of real arrival and departure flights on Zurich Airport (ZRH) which is the largest airport in Switzerland and a hub airport for Swiss International Air Lines AG. The considered data was recorded on 19th October 2007 and included 26 flights arriving or departing between 6:00 and 7:00. The data provided specified landing/pushback times and gates/runway exits for each of the 12 departures and 14 arrivals.

Since the provided dataset of arrivals and departures did not contain the information about the exact aircraft type, the aircraft have been divided into 3 groups according to their wake vortex separation requirements. For each category, a representative aircraft is designated and its specifications are used during the calculation. The specifications are summarized in Table II.

TABLE II
SPECIFICATIONS OF THE REPRESENTATIVE AIRCRAFT.

	Learjet 35A	Airbus A320	Airbus A333
Take-off weight m	8300 kg	78000 kg	230000 kg
Engines	TFE731-2-2B	CMF56-5-A1	CF6-80E1A2
Number of engines	2	2	2
Rated output F_o	2×15.6 kN	2×111.2 kN	2×287 kN
Rolling resistance F_r	1221 N	11.48 kN	33.84 kN
Fuel flow at 7% F_o	0.024 kg·s^{-1}	0.101 kg·s^{-1}	0.228 kg·s^{-1}
Fuel flow at 30% F_o	0.067 kg·s^{-1}	0.291 kg·s^{-1}	0.724 kg·s^{-1}

The computational experiments have been performed on a computer with an Intel i3-2120 processor and 3.16 GB of RAM, running Windows XP. The integrated procedure and the k-QPPTW algorithm are programmed in Java whereas the heuristic and the discretisation subprocedure are written in the Matlab programming language.

Fig. 7 shows the resulting Pareto fronts from the original k-QPPTW algorithm with PAIA [16] which considered all decision variables a_1, d_1, d_2, d_4 and k-QPPTW with the proposed heuristic for speed profile optimisation. To obtain a better coverage of the Pareto front, the heuristic was also used to generate $\ell = 10$ roughly equally spaced solutions (line 2 in Fig. 3). The corresponding running times are shown in Table III. The first two columns provide the running time of the individual components. The third column includes the execution time of the other subprocedures of the integrated procedure (e.g. discretisation of the Pareto front) as well as the overhead caused by the cooperation of Java and Matlab which takes around 85% of this time.

The proposed heuristic for speed profile optimisation could find solutions with better fuel consumption in a significantly shorter time compared to PAIA. The experiments with seeding the initial population generated by the heuristic into PAIA did not produce significantly better solutions compared with the heuristic alone, indicating that the solutions found by the heuristic might be close to the true Pareto front.

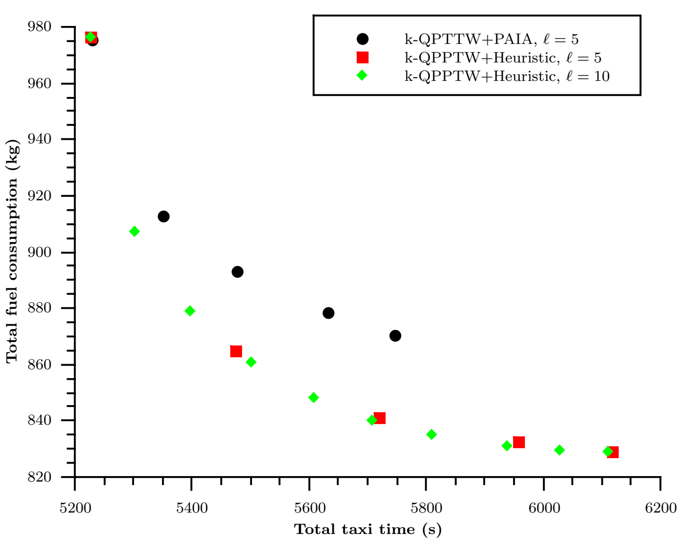


Fig. 7. Global Pareto front of 26 aircraft.

TABLE III
RUNNING TIMES OF ALGORITHMS (MIN.).

Algorithm	k-QPPTW	PAIA/ Heur.	Other	Total
k-QPPTW+PAIA, $\ell = 5$	0.5	305.0	5.2	310.7
k-QPPTW+Heur., $\ell = 5$	0.5	1.4	3.9	5.8
k-QPPTW+Heur., $\ell = 10$	1.0	3.4	8.1	12.5

A comparison of solutions with the minimum fuel burn found by PAIA and the proposed heuristic for a single aircraft taxiing on the given route is shown in Fig. 8. As can be seen from Fig. 8, the proposed heuristic could find a solution with a longer taxi time. However, a close examination of the thrust/brake profile shows a reduced use of thrust at time 0 and 160 s for the solution found by the heuristic which results in lower fuel consumption compared to the solution found by PAIA.

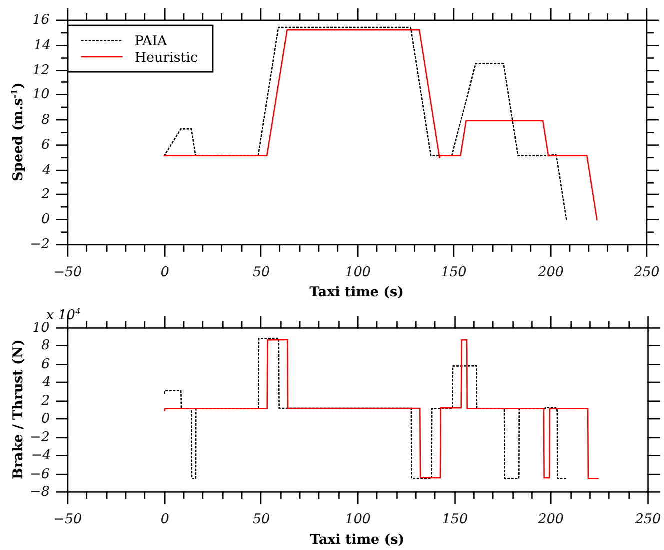


Fig. 8. Slowest speed profile with the best fuel consumption for an aircraft, comparison of solutions found by PAIA and the heuristic.

V. CONCLUSIONS

This paper presented an improved approach to the ground movement problem considering the total taxi time and fuel consumption of aircraft simultaneously. The proposed heuristic for the approximation of the trade-off curve between time and fuel burn for a particular route decreased the computation time of the integrated method and improved the accuracy of the results. These improvements move the proposed approach one step closer towards an on-line decision support system. The analysis of the running time also reveals a potential for reducing the large time overhead which could lead to a faster execution time, especially when deployed on several computers at the same time. However, the proposed heuristic approach for speed profile optimisation is limited to a case when the fuel consumption function meets certain requirements. A better insight into actual fuel burn during all taxiing phases is necessary in order to fully validate the proposed heuristic for speed profile optimisation. Future research will also investigate the possibility of applying a more efficient search algorithm making the approach more general than the heuristic method which was presented in this paper.

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