Towards a More Realistic, Cost Effective and Greener Ground Movement through Active Routing: Part 1-Optimal Speed Profile Generation

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Abstract—Among all airport operations, aircraft ground movement plays a key role in improving overall airport capacity as it links other airport operations. Moreover, ever increasing air traffic, rising costs and tighter environmental targets create a pressure to minimise fuel burn on the ground. However, current routing functions envisioned in Advanced Surface Movement, Guidance and Control Systems (A-SMGCS) almost exclusively consider the most time efficient solution and apply a conservative separation to ensure conflict free surface movement, sometimes with additional buffer times to absorb small deviations from the taxi times. Such an overly constrained routing approach may result in either a too tight planning for some aircraft so that fuel efficiency is compromised due to multiple acceleration phases, or performance could be further improved by reducing the separation and buffer times. In light of this, Part 1 and 2 of this paper present a new Active Routing framework with the aim of providing a more realistic, cost effective and environmental friendly surface movement, targeting some of the busiest international hub airports. Part 1 of this paper focuses on optimal speed profile generation using a physics based aircraft movement model. Two approaches based respectively on the Base of Aircraft Data (BADA) and the International Civil Aviation Organization (ICAO) engine emissions database have been employed to model fuel consumption. These models are then embedded within a mutli-objective optimization framework to capture the essence of different speed profiles in a Pareto optimal sense. The proposed approach represents the first attempt to systematically address speed profiles with competing objectives. Results reveal an apparent trade-off between fuel burn and taxi times irrespective of fuel consumption modelling approaches. This will have a profound impact on the routing and scheduling, and open the door for the new concept of Active Routing discussed in Part 2 of this paper.

Index Terms—Multi-objective optimization, heuristics, active routing, A-SMGCS, fuel consumption models, BADA, ICAO engine emissions database.

I. INTRODUCTION

A recent EUROCONTROL report has stated that an expected increase in total volume of flights will be 1.5 times larger by 2035 than in year 2012 [1]. The growth in air traffic will create pressure on airport capacity thus creating bottlenecks for the entire air traffic management system. Improving the efficiency of surface movement plays a key role in increasing overall airport capacity as it links other airport operations and thus has a knock-on effect. Moreover, air traffic contributes today about 3% to global greenhouse gas emissions, and it is expected to triple by 2050 [2]. Meeting the EU's climate and energy objectives will require reducing drastically the sector's environmental impact by reducing its emissions. Therefore, maximising fuel efficiency to use less to go farther is also a key cost-cutting factor in a very competitive industry [2]. Furthermore, fuel burn is linked to unwanted noise pollution which affects the immediate vicinity of the airport and is subject to legislative constraints.

The last forty years or so have seen a high level of research interest in Operational Research in the Airline Industry in general and surface movement in particular. The main concern of surface movement is to provide guidance to aircraft from the landing runway to the parking position on the apron and back to the runway used for take-off. Evidence reflecting such an interest is the concept of Advanced Surface Movement, Guidance and Control Systems (A-SMGCS) [3]. Comparing to the traditional SMGCS, the use of automation enables elements of the functions, such as control, guidance and automated route assignment, to be realised, and facilitates more precise guidance and control for all aircraft on the movement area over a much wider range of weather conditions. Among four basic functional requirements of A-SMGCS, i.e. surveillance, routing, guidance, and control, the automated routing function plays the most important part in improving time efficiency by providing an optimised route and schedule for each participating aircraft. Also highlighted in A-SMGCS is that fuel efficiency can be improved at the same time through collaboratively optimising the traffic flow of aircraft surface movement with respect to reducing delay, potential conflict, longitudinal spacing, and managing taxi speeds (e.g. through reducing braking and accelerations, hence fuel burn).

As mentioned in [3], with a carefully devised routing function which takes into account realistic taxi speeds and longitudinal spacing, both time and fuel efficiency can be achieved at the same time. However, it is still the case that most surface movement research exclusively considered the most time efficient solution based on assumed constant taxi speeds [4], [5] or bounds [6]-[9], resulting in an unrealistic planning. Consequently, a conservative separation and additional buffer times have to be added to ensure a conflict free taxiing and

absorb small deviations from the taxi times. Assumptions have been made that this will simultaneously mitigate environmental impact and reduce operating costs due to the reduced engine running times. However, recent research has shown that such assumptions may not always be true and potential trade-offs may exist between objectives such as fuel burn, operating costs, delays and system throughput [10]-[12]. Planning based on unrealistic taxi speeds may result in unprecedented conflicts and missing time windows in the real scenario due to variations of pilots' behaviors. This may cost more time and fuel to resolve the problems.

Furthermore, with the development of airport surface surveillance technologies, e.g. the increased availability of Airport Collaborative Decision Making (A-CDM) systems [13], attempts on working towards a connected system, linking airspace and airports, are becoming viable. This leads to readily available information of landing time and aircraft ground position. Increased predictability in airport surface operation management could mean an optimised pushback decision [14] and switching point from a single engine to double engine taxiing [15]-[18]. This also implies that, apart from the conventionally assigned routes and time slots, richer information, such as the optimised speed profiles, could now be 'actively' considered within the routing function and be provided to pilots through the guidance function. Planning based on more realistic and optimal speed profiles lays down a foundation for the guidance function so that high-precision taxiing, meaning a reduced separation and buffer times and increased efficiency, could be achieved.

The overriding objective of Parts 1 and 2 of this paper is hence to introduce a new Active Routing (AR) concept with the aim of providing a more realistic, cost effective and environmental friendly surface movement. At the heart of this concept is optimal speed profile generation taking into account both time and fuel efficiency, which is the main focus of Part 1. The proposed AR framework in Part 2 relies heavily on the generated optimal speed profiles. To the best of our knowledge, the research presented in this paper represents the first attempt to explicitly consider both time and fuel efficiency in a holistic multi-objective speed profile optimisation framework. The novelty of the work also lies in its generality as results suggest that, irrespective of fuel consumption models, the form of the generated speed profiles are mainly determined by the aircraft model and a clear trade-off has always been observed. Such a trade-off will have a profound impact on the solution methods for routing and scheduling. The conclusions made in Part 2 will be mostly retained and the validity of the proposed AR is always held, even in the absence of an accurate ground movement fuel consumption model, as the proposed AR is based on the speed profiles and only the amount of fuel burn will be slightly different. The paper is organised as follows: Section II reviews the evolution of surface management systems and discusses the important role of optimal speed profile generation in the proposed AR framework; Section III introduces a multi-objective speed profile optimisation framework using a physics-based aircraft model; also in this section, two approaches for modelling fuel consumption during ground movement are discussed; the proposed approach has been utilised to generate a set of Pareto optimal speed profiles for a particular route of Manchester Airport in Section IV; a heuristic procedure is proposed in Section V in order to quickly approximate the trade-off curve between the total taxi time and fuel consumption; finally, conclusions are drawn in Section VI.

II. THE EVOLUTION OF SURFACE MANAGEMENT SYSTEMS

The requirements for implementing a variety of surface movement, guidance and control systems extend far back in ICAO's history [19]. Here, 'guidance' relates to facilities, information and advice necessary to enable pilots of aircraft or drivers of ground vehicles to find their way on the aerodrome and to keep aircraft or vehicles on the surfaces or within the areas intended for their use. 'Control' means the measures necessary to prevent collisions and to ensure that the traffic flows smoothly and freely. Despite some basic consent about what SMGCS should include, an over-all review of the subject, using a systems approach, was only undertaken after the Eighth Air Navigation Conference (Montreal, 1974) which established a set of operational requirements to be satisfied by SMGCS. In 1986, the publication of the updated material as a manual marked the beginning of SMGCS and related research activities [19]. However, in SMGCS, the control function is mostly carried out using 'see and be seen' to maintain spacing and avoid collision. Simple visual aids, such as markings, lighting and signs, were made available for the purpose of guidance and were not sufficient in low visibility conditions. Only limited surveillance information and radiotelephony were provided for communication. Route planning and establishment of standard taxi routes were only carried out for high traffic volume operations. In view of this, A-SMGCS published in 2004 [3] aims to utilise more precise surveillance information and automated route assignment so that a conflict free and efficient taxiing can be extended to all weather conditions. Fig. 1 shows the evolution map of surface management systems. For the convenience of discussion, A-SMGCS has been classified into three generations according to:

1) How the 'routing' function is interacting with taxi speeds.
2) Whether the 'guidance' function provides detailed speed profiles apart from the assigned route and its associated time windows.
3) Whether the 'control' function receives feedback information provided by the surveillance system.
4) Whether the generated speed profiles are optimised with respect to different objectives.

Although in Parts 1 and 2 of this paper, the focuses are placed on the routing function, the guidance function is also briefly reviewed for the purpose of completion. More specifically, in Part 1, a detailed discussion is carried out to investigate how taxi speeds were utilised in decision making to generate the assigned route. For a detailed review of the routing and scheduling methods, readers are referred to Part 2 of this paper.
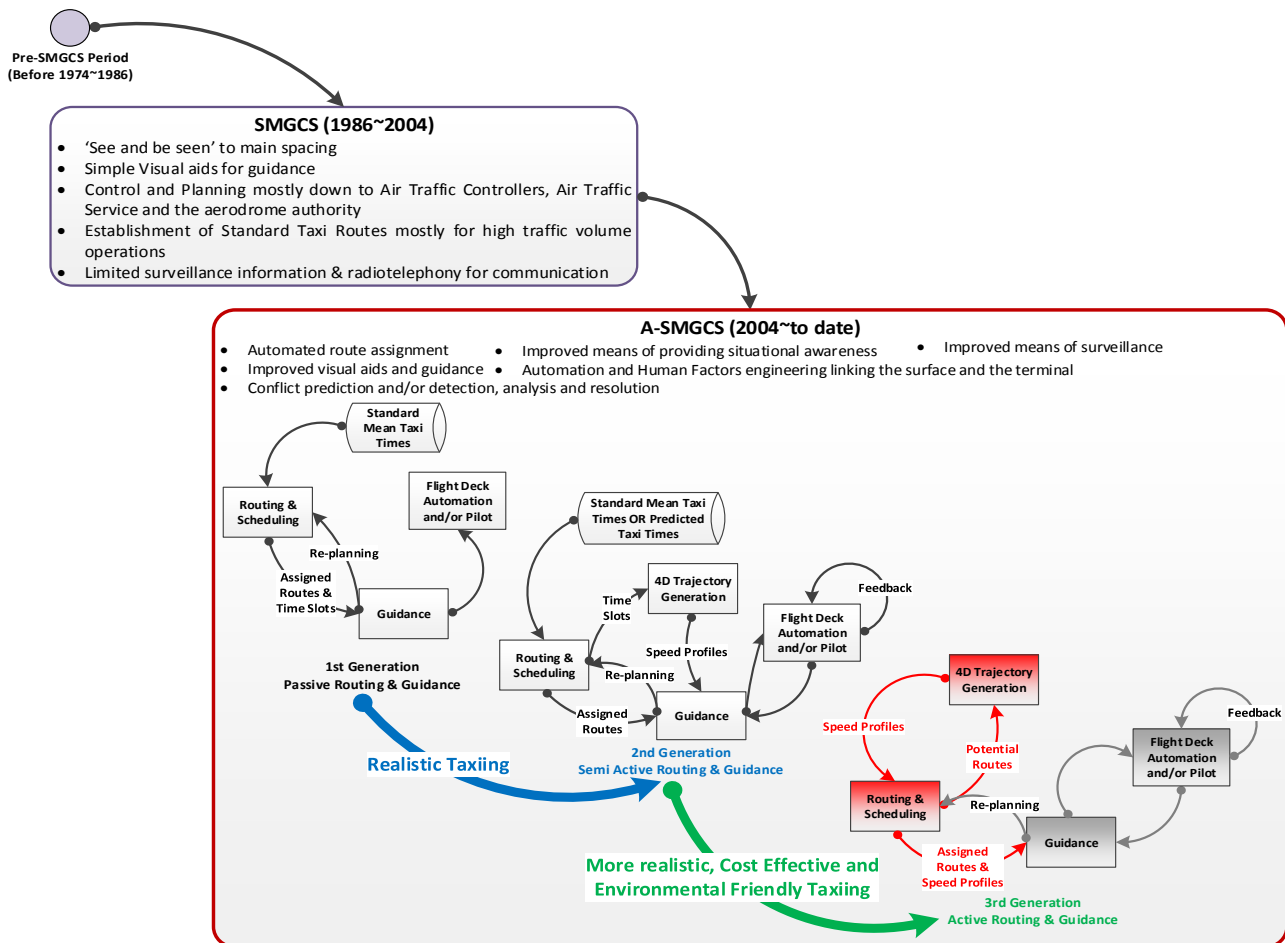
Fig. 1. The evolution of surface management systems (Note: for the 3rd generation of A-SMGCS, the focus of this paper is placed on the Active Routing part).

A. 1st Generation: Passive Routing and Guidance

In the 1st Generation, most research activities within A-SMGCS tends to deal with planning based on standard mean taxi times (or assumed constant speeds and bounds) for specific source/destination pairs, perhaps further broken down into aircraft sizes but usually with no further discrimination [16]. As pointed out by Chen, *et al.* [16], for almost all current routing functions, as any variances from the means were usually considered irrelevant and replaced by the addition of slack time when needed, the resulted planning may either be too tight for some aircraft so that fuel efficiency is compromised due to multiple acceleration phases, or performance could be further improved by reducing separation and the buffer times. Examples of utilizing standard mean taxi times as the basis for route planning can be found in [4]-[9], where the proposed routes and time slots are intended to be provided to controllers and pilots.

Marín formulated the taxi planning problem as a space-time network in [4]. The time used by aircraft to move along each link depends on a fixed average velocity of that link. The objective function aims to minimise the total taxi time in favor of the shortest path where possible. The route planning and scheduling function implemented in NASA's Surface Traffic Limitations Enhancement (STLE) model also utilises a constant link speed [5].

Clare, *et al.* [6] utilised a Mixed Integer Linear Programming method for the coupled problems of airport taxiway routing and scheduling. In their approach, active aircraft are modelled as points moving along the arcs, subject to a maximum speed limit. Each active aircraft is required to move from its specified origin node to its final destination node. As the objective is to maximise throughput, and to minimise the total taxi time and the cost-to-go, the resulted planning tend to move at the maximum speed. No buffer times have been considered, which may potentially offset the benefit when it is applied to real scenarios. Small deviations from the planned speeds may require a complete re-planning. It is also worth mentioning that for some arcs of the planned route, such as the turning arcs, aircraft has to traverse at much lower speeds. Therefore, whether the planned time slots for those segments are realistic in practice without involving excessive acceleration and deceleration is questionable. A similar approach can be found in [7] where both maximum and minimum times needed for aircraft to taxi along the edge of its routes are used as the constraints. Unlike [6], the upper and lower time bounds can vary depending on whether the edge is a turn or a straight segment, which make the planned solution more realistic for pilots to follow. However, as in each segment, aircraft still tend

to taxi at their maximum speeds, how this will affect the use of acceleration and deceleration in practice is unknown. In [8], the maximum speed of an aircraft on a taxi link is bounded by a constant depending on the location of the link. As pointed out by Lesire [9], most of the approaches in the 1st generation do not consider feasibility of the ground movements that correspond to the given scheduling. The resulting itineraries, represented by sequences of timed nodes, are not realistic. The hypothesis is that the aircraft speed is constant on each edge, leading to a discontinuous speed evolution of aircraft along its trajectory. In order to deal with discontinuous speed, a speed uncertainty of 3 m·s^{-1} has been added to the cost function in [9] to allow certain flexibility in planning.

As accurate speed and position information are not available and considered explicitly in the routing function, the above approaches are classified into the 1st generation: 'Passive Routing and Guidance'. Lesire [9] pointed out that route planning is intended to be used on-line to plan itineraries for aircraft moving on an airport so that these itineraries (sequel of points with time intervals) could be used either by human controllers, pilots, or by an automatic control law to control the aircraft speed along the trajectory. Therefore, in the next section, we will see a moving trend towards how to improve the realism of routing and guidance.

B. 2nd Generation: Semi Active Routing and Guidance

In light of the above drawbacks in the 1st Generation, developments in [20]-[26] started to consider either realistic taxi speed predictions or detailed speed profiles respecting time intervals given by the routing function for realistic guidance.

In [20], [21], a new sequential graph-based algorithm is introduced. Both a statistical approach and a Fuzzy Rule-Based Systems approach have been adopted to estimate aircraft taxi times using historical landing and departure times. Both estimation approaches lead to more accuracy than a standard lookup table. As the decision variables are extracted using the same directed graph representation of the airport, the predicted unimpeded taxi-in and out times, hence the speeds, are used as the basis for calculating the transversal times on each edge, leaving interactions of aircraft to be dealt with by the routing and scheduling function. It is believed that in this way the generated planning is realistic for pilots to follow as it is based on past operational experience. However, it is worth pointing out two potential problems pertaining to this approach: a) historic data only reflects past operational modes prior to further optimization; whether such knowledge is valid to be reused for optimal solutions under unencountered scenarios, if so, to what extent, remains unknown; b) historical data may be biased towards the situation where an aircraft is impeded as this is more often the case in real scenarios, and hence may not be sufficient to predict the unimpeded situation.

Instead of improving the realism of the planned route and schedule, another line of research attempts to improve realism of the guidance function by generating speed profiles within the guidance system [22]-[26]. In [22], [23], increased timing precision and reduced aircraft spacing is achieved through the concept of Surface Trajectory-Based Operations (STBO). The required time of arrival (RTA) algorithm dynamically computes the advised speeds by accounting for remaining distance, remaining time to RTA, and the number of turns, with assumed acceleration/deceleration rate of $1 \text{ kn} \cdot \text{s}^{-1}$ and turn speed of 10 knots. The initial advised straightaway speed is 15 knots. The RTA algorithm then dynamically compensates for the pilot slowing down or speeding up by appropriately increasing or decreasing the advised straightaway speed using the feedback control theory. In [24]-[26], under the concept of Surface Operation Automation Research (SOAR), the Flight-deck Automation for Reliable Ground Operation (FARGO) re-creates the cleared 4D route from the data-link message sent by the routing function, and generates a reference trajectory that defines position, velocity and acceleration as functions of time to meet the crossing constraints. Factors to be considered in generating speed profiles include turn radii, hold distances, aircraft performance, passenger comfort, etc. Furthermore, in the current FARGO prototype, it imposes additional model behaviors for the velocity profile, e.g. a constant speed in intersections depending on dimensions of the intersections and aircraft itself. However, as stated in [26], many degrees of freedom still exist in the current speed profile generation approach, resulting in non-unique speed profiles. Several problems associated with this line of research can be summarized as follows:

1) As indicated in Fig. 1, speed profiles are only generated after a set of conflict-free taxi clearances, containing required times of arrival to significant control points on the surface; the generated speed profiles are considered as results of the guidance system and have no influence on the routing and scheduling function.
2) As the generated speed profiles are not optimized and interact with the routing and scheduling function, the resulted 'optimal' route and schedule are also not optimal.
3) There are still many degrees of freedom in generating speed profiles, which will have different accelerations and in turn will have different emissions and fuel consumptions. Although a clear trade-off has been observed between different speed profiles [26], the current FARGO approach, for example, does not provide a systematic approach to define and select a unique optimal speed profile with respect to different objectives.

As realistic speeds are either considered only in the routing and scheduling function without further optimization, or generated in the guidance function without influence on the routing and scheduling results, the above approaches are classified into the 2nd generation: 'Semi Active Routing and Guidance', to reflect the fact that detailed optimal speed profiles are not independently defined, and proactively considered in both routing and guidance functions.

C. 3rd Generation: Active Routing and Guidance

Both in European's 'Single European Sky Air Traffic Management' (SESAR) [27] and the USA's 'Next Generation Air Transport System' (NextGen) [28], it is conceived that the introduction of complete 4-Dimensional trajectories (4DTs),

representing the aircraft path consisting of three space dimensions plus time, will form the major cornerstone of air traffic research and facilitate gate to gate operation. It is also predicted that the introduction of 4DTs on the ground would significantly reduce taxi delay up to 55% [29]. However, in the context of ground movement, not all dimensions are required as aircraft move on airport surface. In this case, it is sufficient to completely define their position in time with routes and speed profiles. As a result, for consistency and clarity, speed profile is the term used throughout the paper, which in some cases when combined with routes, is interchangeable with 4DTs as used in [27], [28]. As discussed in Section II.B, the potential benefit of speed profiles has not been fully exploited. Recently, a moving trend towards the 3rd generation has seen the utilization of optimised speed profiles, which are generated with respect to different objectives and are proactively embedded within the routing and scheduling function [10], [12]. The benefits from such a seamless integrated approach are two-fold:

1) As speed profiles are optimised regardless of the time constraints given by the routing and scheduling function, and can be embedded within the routing and scheduling function, a more optimal surface movement mode may be discovered.
2) More objectives, such as fuel burn, passenger comfort, noise, pollution and pilot behavior, can now be accommodated in a more systematic and unified optimization framework, which will ultimately increase the realism of the generated planning.

The work presented in Parts 1 and 2 of this paper is an extended work based on [10], [12]. In the following sections, particular attention has been given to how to generate optimised speed profiles with respect to two objectives, namely minimising both taxi times and fuel consumption. However, the proposed framework can be extended further to accommodate more objectives.

III. MULTI-OBJECTIVE OPTIMAL SPEED PROFILE GENERATION

The aim of optimal speed profile generation is to obtain a set of complete speed profiles, in a Pareto optimal sense, defined by corresponding unimpeded speed profiles Y_i for aircraft i taxiing on the route q_l. Two objectives considered in this paper are defined in (1).

$$\begin{aligned} g_1 &= T(q_l, y_i) \\ g_2 &= F(q_l, y_i, w_i) \end{aligned} \qquad (1)$$

where, $T(q_l, y_i)$ is a function which returns travel time of aircraft i taxiing unimpededly for a given speed profile $y_i \in Y_i$; here, y_i is a function of time; similarly, $F(q_l, y_i, w_i)$ is a function which returns the amount of fuel burn during taxiing for aircraft i, under the weight category w_i. The problem formulated here intends to investigate how to taxi not only in a timely manner but also in a fuel efficient way, taking into account three factors: the characteristics of the taxiway, thrust levels dictated by the given speed profile, and the specification of the aircraft such as its weight, engine type, drag, rolling

resistance, etc.

One of the distinctive features of the proposed framework is that, for g_2, an average value for fuel flow is not assumed during taxiing. Instead, we explicitly account for fuel consumption as a continuous function of variations in speed. Similar ideas can be found in [30], in which four fixed thrust levels, corresponding to four different phases, are assumed. The fuel consumption is then calculated by multiplication of the time spent in each phase with the corresponding fuel flow. Obviously, the approach proposed in [30] is constrained and sensitive to the assumed thrust levels, and provides little room in search of more efficient operational modes in order to improve current surface movement practices.

In order to systematically investigate the potential best practice of taxiing under different thrust settings, in the following sections, we first model the taxiing procedure as a discretized piece-wise linear speed profile. Based on the aircraft longitudinal motion model, the thrust level as a function of time during the entire taxiing can be uniquely determined for a given speed profile. Fuel consumption is thus estimated using two approaches based respectively on the Base of Aircraft Data (BADA) [31] and the International Civil Aviation Organization (ICAO) engine emissions database [32]. The obtained decision variables, constraints and two objectives will then be used in a metaheuristic multi-objective optimisation framework, such as algorithms in [33], [34], and [35] to generate optimal speed profiles.

A. Speed Profiles and the Taxi Time Modelling

In order to model unimpeded taxiing procedure along the given route q_l, as shown in Fig. 2, the route is further divided into large segments, each containing several edges. For example, several consecutive straight edges typically form one straight segment. The turning segment consists of consecutive edges between which have an angle of at least 30 degrees.
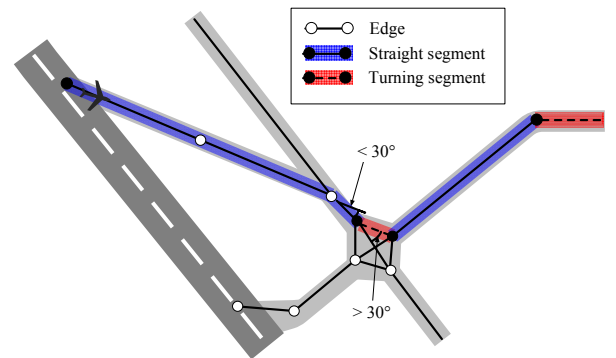

Fig. 2. An example of segments consisting of edges for a taxiway at Manchester Airport.

As aircraft can taxi with speed as a continuous function of time along each segment, it gives rise to infinite degrees of freedom. In order to further reduce the complexity of the speed profile optimisation problem, each straight segment of the route is decomposed into four parts, corresponding to four different aircraft taxiing phases, i.e. acceleration, travelling at constant speed, braking and rapid braking, representing a typical taxiing

behavior as illustrated in Fig. 3. Inherently, this decomposition effectively models a good driving practice without excessive use of acceleration and deceleration, while still maintaining time efficiency. Therefore, further optimisation is reduced to only find out optimal switching times of different phases.
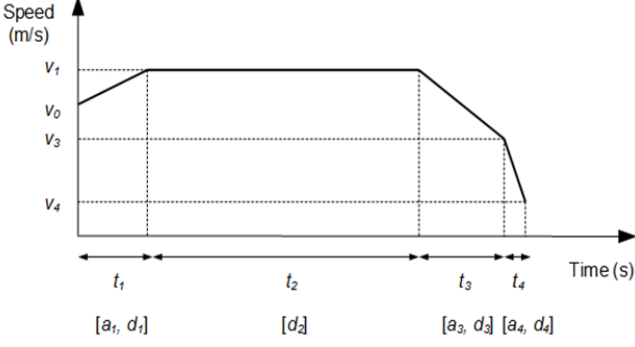

Fig. 3. An example of a speed profile with four phases.

The first phase is the acceleration 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 phases, 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 and turning speed v_{turn} is set to 10 knots as in [3]. 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, similar as in [36].

As a result, there are four independent variables a_1, d_1, d_2, d_4 which define a unique speed profile over a segment s. The taxi time (TT_s) needed to traverse a single segment is the sum of the time t_j spent in the different phases.

$$TT_s = \sum_{j=1}^{4} t_j. \qquad (2)$$

where, t_j is defined in Section III. C. For the entire route q_l, four independent variables defined above for individual segment will be concatenated to form the complete set of decision variables. By searching for values of these variables, one can explore different speed profiles with different taxi time and fuel consumption. Objective g_1 can now be rewritten as:

$$g_1 = \sum_{s \in q_l} TT_s. \qquad (3)$$

B. Aircraft Motion Model and Fuel Consumption Modelling

In order to calculate fuel consumption (g_2) of the participating aircraft, its longitudinal motion model is derived using Total Energy Model (TEM) defined within BADA [31] by considering the following forces: thrust T generated by the engines, normal force, rolling resistance of tyres F_r and aerodynamic drag D as depicted in Fig. 4. Therefore, the longitudinal motion model is given in (4):

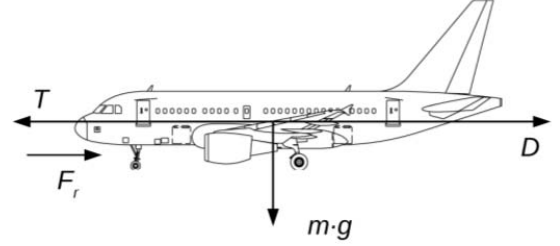$$T = m \cdot a_1 + F_r + D. \qquad (4)$$

Fig. 4. Forces acting on aircraft during taxiing.

Where, F_r is proportional to the rolling resistance coefficient μ and normal force $m \cdot g$ as given in (5), where $g = 9.81$ m·s^{-2}, and m is the aircraft weight given by its weight category w_i. The coefficient μ is suggested to be around 0.02 for aircraft tyres [37]. In this paper, μ is set to 0.015 for concrete surface. Values between 0.015~0.02 are also in good conformance with the ICAO idle thrust setting of 5%~7% [32].

$$F_r = \mu \cdot m \cdot g. \qquad (5)$$

Drag induced by moving aircraft through air depends on the density of air ρ, speed v of aircraft, its wing area S and drag coefficient C_D as defined in [31]:

$$D = \frac{1}{2} C_D \cdot \rho \cdot v^2 \cdot S. \qquad (6)$$

Given a particular speed profile y_i corresponding to a particular route q_l, the associated thrust T is defined by (4). Given T, fuel consumption can be modelled using two different methods:

1) Method based on ICAO emission database

The method based on ICAO emission database further simplifies thrust calculation by not taking drag D into account in (4). T and maximum power output F_0 of the engine is used to calculate the thrust level ε:

$$\varepsilon = \frac{T}{F_0}. \qquad (7)$$

As mentioned in Section III.A, four phases are defined for a straight segment: acceleration, constant speed, braking and rapid braking. Equation (6) is used for acceleration and constant speed phase. During braking and rapid braking, we assume $\varepsilon = 5\%$. For turning, $\varepsilon = 7\%$. The fuel flow f_j corresponding to the thrust level ε is obtained by linear

interpolation/extrapolation using reported fuel flows from ICAO emission database at 7% and 30% similarly as in [30]. Finally, the fuel consumption ($fuel_s^{ICAO}$) for the segment s is obtained by multiplication of fuel flow f_j for the specific phase j and the time t_j spent in this state:

$$fuel_s^{ICAO} = \sum_{j=1}^{4} f_j \cdot t_j. \tag{8}$$

2) Method based on BADA

BADA specifies the fuel consumption for nominal and idle thrust situations. The nominal fuel consumption f_{nom} corresponds to acceleration and the constant speed phase. The minimum fuel consumption f_{min} is used during braking and rapid braking. The nominal fuel consumption f_{nom} for aircraft with jet engines is a function of the thrust specific fuel consumption θ and T:

$$f_{nom} = \frac{1}{60 \cdot 10^3} \cdot \theta \cdot T. \tag{9}$$

θ corresponds to the flow rate of fuel required to produce a unit of thrust and is a function of speed v and thrust specific fuel consumption coefficients C_{f1} and C_{f2}:

$$\theta = C_{f1} \cdot \left(1 + \frac{v}{C_{f2}}\right). \tag{10}$$

The minimum fuel consumption f_{min}, originally intended for idle-thrust descent calculations, is a function of the altitude h and engine specific descent fuel flow coefficients C_{f3} and C_{f4}. During ground movement, the altitude of the aircraft is assumed to be equal to the altitude of the airport.

$$f_{min} = \frac{1}{60} \cdot C_{f3} \cdot \left(1 - \frac{h}{C_{f4}}\right). \tag{11}$$

For the acceleration phase, the fuel consumption f_1 is calculated by integrating (9), using (4) for T, where speed $v = v_0 + a \cdot t$ and t_1 is the acceleration time:

$$f_1 = \int_0^{t_1} f_{nom} \, dt. \tag{12}$$

For the constant speed phase, the fuel consumption f_2 is calculated by multiplying f_{nom} with corresponding time t_2:

$$f_2 = f_{nom} \cdot t_2. \tag{13}$$

For the braking and rapid braking phase, the fuel consumption f_3, f_4 is calculated by multiplication of minimal fuel flow f_{min} for the specific phase j with the time t_j spent in this state:

$$f_j = f_{min} \cdot t_j, \quad j = 3, 4. \tag{14}$$

The fuel consumption ($fuel_s^{BADA}$) for the segment s is obtained as a sum of fuel burn during different phases:

$$fuel_s^{BADA} = \sum_{j=1}^{4} f_j. \tag{15}$$

Finally, total fuel consumption for the entire route q_l is calculated as follows:

$$g_2 = \sum_{s \in q_l} fuel_s. \tag{16}$$

C. A Metaheuristic Multi-objective Optimisation Framework

For the multi-objective speed profile optimisation problem introduced in Section III.A and III.B, population based metaheuristic algorithms are often cited as very suitable [33], [34], [35]. This type of search algorithms can easily incorporate additional objectives and constraints without the need to change the existing problem formation. Constraints pertaining to this particular problem will be discussed later in this section. Fig. 5 describes the general procedures involved in a multi-objective metaheuristic optimization framework in order to address the problem in this paper. It is to be noted that although the quality of the solutions may differ due to the search capability of a particular search algorithm, the speed profile optimization problem modelled in this paper does not depend on any specific metaheuristic implementation.

1:	Generate the fastest speed profile for all segments;
2:	Generate initial population around this solution;
3:	**For** $gen = 1$ **to** gen_{max} **do**:
4:	**non-dominated sorting and selection:** candidate solutions will be evaluated according to Equations (3) and (16) and fitness values will be assigned to each solution;
5:	**Reproduction:** good candidate solutions will have more chance to be reproduced depending on the selection schemes;
6:	**Constraint handling:** reproduced solutions will be checked for constraint violations according to Equation (17) to (29);
7:	**Next generation** different elitism and diversity preservation schemes can be employed;
8:	**End**

Fig. 5. Optimal speed profile generation using a multi-objective metaheuristic framework.

In order to speed up the search, a solution with the shortest taxi time for the given route q_l is first analytically derived in line 1. Such a solution corresponds to the situation where $a_1 = a_4 = a_{max}$, $d_1 = d_1^u$, $d_2 = d_2^u$, $d_3 = 0$, and $d_4 = d_4^u$. Definitions of d_1^u, d_2^u, and d_4^u will be explained in the remaining of this section. The generated solution is then seeded into the initial population. The rest of the initial population is filled by solutions randomly generated around the seeded solution (line 2). The algorithm iterates for gen_{max} iterations (lines 4-8). Solutions are evaluated in line 4 in terms of the taxi time and fuel consumption and non-dominated sorting is performed. Fitness assignment and selection are also carried out. Reproduced candidate solutions will be checked for constraint violations (line 6). The output of the algorithm is an approximation of the Pareto front. Although different schemes for fitness assignment, selection, and reproduction can be

implemented and will impose different search capability, the focus of this paper is not on a particular optimisation algorithm implementation. In Section IV.C, the well-known NSGA2 [35] and a Population Adaptive Immune Algorithm (PAIA) [33], [34] are employed as the search engine for this problem..

As mentioned above, the decision variables have to satisfy physical constraints in order to be feasible. The constraints are determined in a sequential manner where once a constraint has been calculated it serves as an input for the next computation:

(1) The upper bound a_1^u equals to the maximum acceleration a_{max}. The lower bound a_1^l corresponds to a situation when the aircraft constantly accelerates over the entire segment. a_1^l must ensure that at the end of the segment v_4 can be reached:

$$a_1^l = \frac{v_4^2 - v_0^2}{2d}. \tag{17}$$

(2) The bounds for d_1 are determined after a_1 has been fixed during the search. The lower bound d_1^l must be long enough to allow reaching the speed v_4 at the end of the segment:

$$d_1^l = \frac{v_4^2 - v_0^2}{2a_1}. \tag{18}$$

The upper bound d_1^u is determined by a_1 and the longest possible acceleration time t_1. Otherwise, aircraft will not be able to decelerate even with a_{max} to the required v_4:

$$d_1^u = v_0 \cdot t_1 + \frac{1}{2} a_1 \cdot t_1^2. \tag{19}$$

Depending on the length d of the segment, aircraft may or may not have enough acceleration time t_1 to reach the maximum speed $v_{straight}$. Therefore, d needs to be checked first. The shortest length d_{min} that is sufficiently long to reach $v_{straight}$ and then brake with a_{max} to reach v_4 is defined in Equation (20).

$$d_{min} = \frac{v_{straight} + v_0}{2} \cdot t_1 + \frac{v_{straight} + v_4}{2} \cdot t_4. \tag{20}$$

Where t_1 and t_4 are times to accelerate to $v_{straight}$ or decelerate to v_4 respectively with a_{max} and can be calculated as follows:

$$t_1 = \frac{v_{straight} - v_0}{a_1}. \tag{21}$$

$$t_4 = \frac{v_{straight} - v_4}{a_{max}}. \tag{22}$$

This leads to two different scenarios for calculating t_1:

a) $d > d_{min}$: In this case, t_1 is the time for the aircraft to accelerate until it reaches $v_{straight}$. Therefore, Equation (21) holds in this scenarios for calculating t_1. Substituting (21) into (19) gives the upper bound d_1^u.

b) $d \leq d_{min}$: In this case, d_1^u corresponds to the situation where the aircraft will accelerate with a_1 until it reaches $v_1 \leq v_{straight}$ and then it has to decelerate with a_{max} in order to satisfy constraint at the end of the segment, i.e. v_4. As there are only the first (acceleration) phase and the fourth (maximum deceleration) phase involved in this scenario, the corresponding end speeds for these two phases are defined by (23) and (24).

$$v_1 = a_1 \cdot t_1 + v_0. \tag{23}$$
$$v_4 = v_1 - a_{max} \cdot t_4. \tag{24}$$

Therefore

$$t_1 = \frac{v_4 + a_{max} \cdot t_4 - v_0}{a_1} \tag{25}$$

As there are only two phases involved, d is defined in (26).

$$d = \frac{v_0 + v_1}{2} \cdot t_1 + \frac{v_1 + v_4}{2} \cdot t_4. \tag{26}$$

Substituting (23) and (25) into (26), t_4 is defined in (27).

$$t_4 = \frac{-\left(\frac{a_{max}}{a_1} \cdot v_4 + v_4\right) + \sqrt{\left(\frac{a_{max}}{a_1} \cdot v_4 + v_4\right)^2 + 4\left(\frac{a_{max}^2}{2a_1} + \frac{a_{max}}{2}\right) \cdot \left(d - \frac{v_4^2 - v_0}{2a_1}\right)}}{2\left(\frac{a_{max}^2}{2a_1} + \frac{a_{max}}{2}\right)} \tag{27}$$

Substituting (27) back to (25), t_1 is now completely defined for this scenario, and d_1^u is calculated using (19).

Once d_1 has been fixed during the search within its feasible bounds, v_1 is also fixed and can be used to determine d_2^u and d_2^l:

$$d_2^u = d - d_1 - \frac{v_1^2 - v_4^2}{2 \cdot a_{max}}. \tag{28}$$

$$d_2^l = d - d_1 - \frac{v_1^2 - v_4^2}{2 \cdot a_{min}^d}. \tag{29}$$

where a_{min}^d is defined in (30) and represents the situation where there is only one deceleration phase with a small deceleration rate a_{min}^d and aircraft has to decelerate earlier.

$$a_{min}^d = \frac{v_1^2 - v_4^2}{2 \cdot (d - d_1)}. \tag{30}$$

The upper bound of d_2 represents the situation where d_3 does not exist and aircraft has to decelerate with a_{max}. Finally, after determining d_2 within its feasible bounds d_4^u is calculated according to (28) which refers to the situation when d_3 does not exist. The lower bound d_4^l is set to 0.

$$d_4^u = \frac{v_1^2 - v_4^2}{2 \cdot a_{max}}. \tag{31}$$

During optimisation, all these constraints for all candidate solutions will be checked. If violation has been detected for any decision variables, they will be corrected to the nearest bounds for validity purpose. Additional constraints to handle interactions among multiple aircrafts and safety distance between aircrafts are not included in speed profile generation as they are imposed and will be different considering different routing and scheduling implementation. Keeping speed profile generation fairly independent from the routing and scheduling makes the proposed approach more general and readily adapted to different routing and scheduling solution methods. Readers are referred to Part 2 of this paper for such constraints.

IV. COMPUTATIONAL RESULTS

In this section, the proposed multi-objective optimal speed profile generation approach is applied to generate Pareto-optimal speed profiles for a particular route at Manchester Airport, United Kingdom, as an example.

A. Airport Surface Representation

The airport surface is represented by an undirected graph as shown in Fig. 6 with a highlighted route of arriving aircraft from runway 23R to gate 245. The elevation of the taxiway is $h = 78$ m above the sea level.
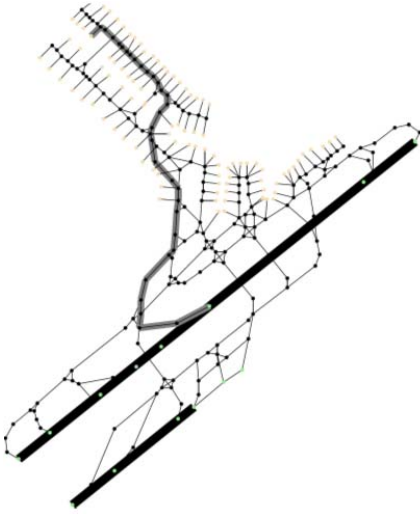

Fig. 6. Graph representation of Manchester Airport with a highlighted route.

The route is divided into segments as given in Table I. As it is an arriving aircraft, the initial speed v_0 at the beginning of Segment 1 will be 10 knots. In order to traverse along this straight segment, a variety of speed profiles are available. The aircraft will exit Segment 1 with a speed $v_4 = 10$ knots which is the initial speed v_0 for Segment 2. Since Segment 2 is a turning segment, aircraft will keep constant speed v_{turn} set to 10 knots. For the last Segment 14, as it is a straight segment with parking, the aircraft will reduce its speed to 0. Although not investigated in this paper, some aircraft may cross an active runway during their ground movement and be required to stop before crossing the runway. In such case, v_4 of corresponding segment would be set to 0 and additional constraints as described in Section III.C will ensure that the aircraft starts its movement only when

it is safe to do so. However, experiments with an active runway crossing remain for the future work.

TABLE I
SEGMENT PROPERTIES

Segment number	Segment type	v_0 (kn)	v_4 (kn)	Length (m)
1	Straight	10	10	429
2	Turning	10	10	82
3	Straight	10	10	199
4	Turning	10	10	197
5	Straight	10	10	38
6	Turning	10	10	90
7	Straight	10	10	270
8	Turning	10	10	57
9	Straight	10	10	146
10	Turning	10	10	127
11	Straight	10	10	237
12	Turning	10	10	147
13	Straight	10	10	464
14	Straight parking	10	0	76

B. Aircraft specifications

As an example, fuel consumption is calculated for an Airbus A320 aircraft with the specifications given in Table II. The A320 is used as a representative medium weight category aircraft in this study.

TABLE II
AIRBUS A320 SPECIFICATIONS

Takeoff weight m	78000 kg
Engines	CMF56-5-A1
Number of engines	2
Rated output F_0	2×111.2 kN
Rolling resistance F_r	11.48 kN
Fuel flow at 7% F_0	0.101 kg/s
Fuel flow at 30% F_0	0.291 kg/s
Drag coefficient C_D	0.02
Wing area S	122.4 m^2
Coefficient C_{f1}	1 kg/(min·kN)
Coefficient C_{f2}	50000 kN
Coefficient C_{f3}	9.4 kg/min
Coefficient C_{f4}	90000 ft

C. Results

In order to generate Pareto optimal speed profiles for the given route, both NSGA2 and PAIA have been adapted according to Fig. 5. NSGA2 serves as the baseline algorithm for the comparison purpose. For a fair comparison, the number of evaluations for both algorithms is set to 12000. This is an empirical number for both algorithms to be fully converged. For NSGA2, user specified parameters are set according to [34] as follows: the population size is 100; crossover probability/fraction is 1, and distribution parameter for simulated binary crossover is 1; mutation probability/fraction is set to 0.018, and distribution parameter for polynomial mutation is 1; the maximum mutation magnitude is 0.1. For PAIA, the initial population size is 7, same as in [16]. Other user specified parameters are set according to [33], [34] as follows: maximum clonal size is 95, clonal selection threshold is 0.4 and network suppression threshold is set to 0.008. Two performance metrics [38] are investigated in this paper: a) the

Generational Distance (GD), which measures the closeness of the obtained Pareto solution set; and b) Spread (Δ), which measures the diversity of the solutions along the Pareto front in the final population. In order to derive statistical significance of differences in performances of both algorithms, Student's *t*-test with significance level 0.05 is carried out. The number of trials for both algorithms is 30. Table III summarises the results.

TABLE III
COMPARISON RESULTS BETWEEN NSGA2 AND PAIA BASED ON GD AND Δ

	g_2 based on ICAO		g_2 based on BADA	
	GD	Δ	GD	Δ
NSGA2	0.0733	0.8053	**0.1553**	0.8206
PAIA	**0.0723**	**0.6762**	0.1673	**0.7490**
Significance	Not Sig.	Sig.	Sig.	Sig.

From Table III, it can be seen that PAIA outperforms NSGA2 in Δ no matter what fuel consumption model is adopted. NSGA2 outperforms PAIA only in GD in one occasion where fuel consumption is modelled based on BADA. As in Part 2 this Pareto front will be discretised into l equally spaced solutions, better performance in Δ will be favoured. Furthermore, if more objectives are considered in speed profile generation in the future, such as emissions, and when decision variable space is biased, PAIA demonstrated superiorities over NSGA2 based on benchmark test problems, such as DTLZ suite [39]. Therefore, PAIA is the solution method for the results shown in the rest of the paper.

Fig. 7 shows the obtained Pareto fronts using two fuel consumption calculation methods described in Section III.B and aircraft specifications given in Section IV.B.
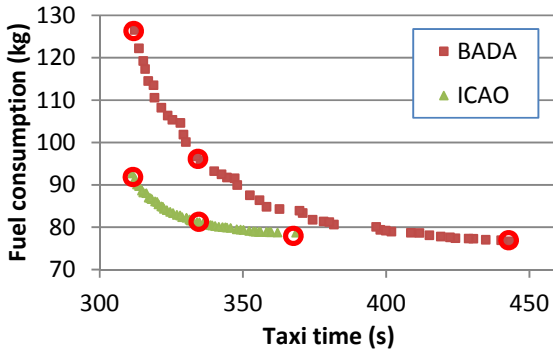

Fig. 7. Pareto fronts of optimal speed profiles based on ICAO and BADA.

For solutions highlighted in Fig. 7, Table IV gives values of $g_1, g_2, \sum T \cdot t_1$ summed for all segments.

TABLE IV
TRADE-OFF ANALYSIS

ICAO			BADA		
g_1 (s)	g_2 (kg)	$\sum T \cdot t_1$ (N·s)	g_1 (s)	g_2 (s)	$\sum T \cdot t_1$ (N·s)
310	93	5.76E+06	310	127	5.19E+06
330	82	3.79E+06	330	100	3.26E+06
369	79	1.96E+06	369	84	1.68E+06
-	-	-	443	77	5.88E+05
+16%	-15%	-64%	+43%	-39%	-89%

A clear trade-off has been observed in both Fig. 7 and Table IV. The results confirm that the most time efficient solution is the least fuel efficient one with a lot of acceleration events expressed by high values of $\sum T \cdot t_1$, and vice versa. As the BADA method is optimised for aircraft in cruise, it may introduce inaccuracies at lower altitudes/airspeeds and on ground, which will potentially lead to an overestimation of fuel burn. The ICAO method is widely adopted for ground fuel burn estimation [30]. However, the interpolation between 7% and 30% may also introduce inaccuracies. Surface fuel consumption models with high fidelity are crucial as they will have influence on environmental benefit assessment for any automated airport surface management systems. However, accurate fuel burn estimation is outside the scope of this paper. Conclusions drawn in this paper still hold as Table IV reveals that, regardless of fuel consumption models, values of $\sum T \cdot t_1$, corresponding to the same value of g_1, are very similar. This is due to the fact that g_1 is is directed linked to the speed, which is dictated by thrust levels. Furthermore, thrust levels have obvious implication on fuel burn, which is linked to g_2. The speed profile generation problem formulated in this paper is trying to search for the optimal speed profiles by optimising the thrust use. As long as the relationship between thrust levels and g_2 is not highly nonlinear, the accrual fuel burn will not have a significant impact on the generated speed. This effectively means that although the proposed optimal speed profile generation approach may yield noticeable difference in fuel burn quantification with different fuel consumption models, the generated optimal speed profiles, given the same value of g_1, tend to be intrinsically similar. This is a promising feature of the proposed method as the generated optimal speed profiles could be used in practice to route and schedule aircrafts even if the accurate fuel consumption model is not available.

A visual inspection of different optimal speed profiles and corresponding thrust/brake values using different fuel calculation methods also confirms the above conclusion. Due to space limitation, only solutions corresponding to the fast taxiing ($g_1 = 310$ s) and the modest taxiing ($g_1 = 330$ s) are shown in Fig. 8 and 9.
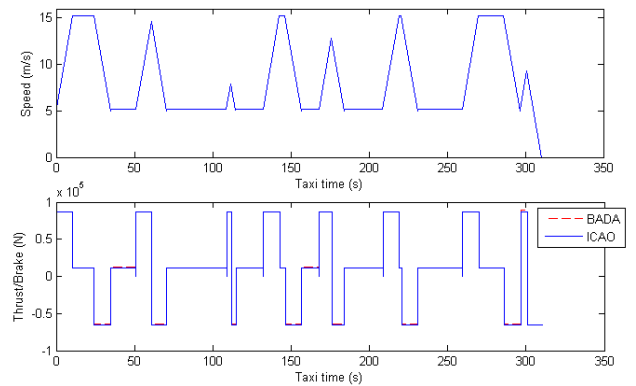

Fig. 8. The fastest speed profiles ($g_1 = 310$ s) with the most fuel consumption.

The close examination of thrust profiles reveals that drag D considered in (6) has little effect on the thrust. For example, the drag for a speed of 30 knots is only 0.3 kN. The difference in g_2 for the fastest solution as shown in Table IV lies in the different

mapping of thrust to fuel burn for different fuel consumption calculation method. This similarities in speed and thrust/brake is further supported by Fig. 9 and held for other solutions.
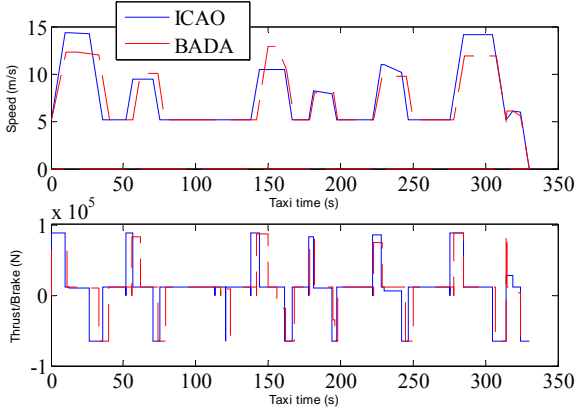

Fig. 9. Speed profiles with g_1=330 s obtained by different fuel calculation methods.

Another interesting observation from Fig. 7 and Table IV is that the proposed speed profile generation approach tends to give solutions with a much wider spread in g_1 when BADA is used. In order to investigate the reason for such a difference, a comparison of the generated most fuel efficient solutions using ICAO and BADA respectively are shown in Fig. 10.
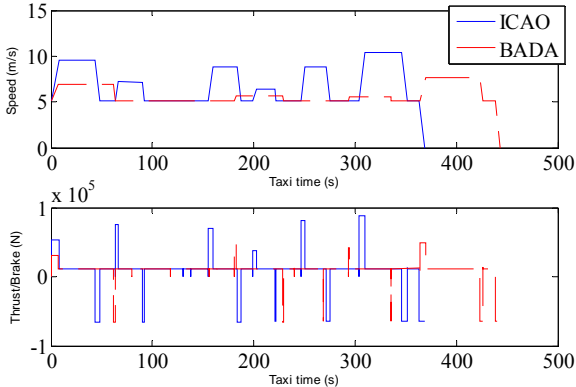

Fig. 10. The slowest speed profiles with the best fuel consumption using ICAO ($g_1 = 348$ s) and BADA ($g_1 = 443$ s).

The reason behind this lies in the ratio of fuel burn during acceleration and constant speed phase. For the method based on ICAO emissions database, the fuel flow f_2 during the constant speed is 23% of the fuel flow f_1 during the maximum acceleration a_{max}, whereas in the case of BADA, f_2 is 13% of f_1. The lower ratio adopted in BADA is weighted in favour of shorter fuel intensive acceleration (resulting in lower speed) in return of longer constant speed phases. Since the ratio is lower for BADA, the trade-off is more significant than that of the method based on ICAO emissions database. This suggests that for accurate ground fuel burn estimation, an accurate estimation of f_2 is paramount. Furthermore, in design of aircraft engine, as reducing fuel flow during the constant speed may provide wider operational range for the benefit of the operational side, this may provide another design specification for optimal engine design.

V. A Heuristic Approach for Optimal speed profile Generation

As the optimal speed profile generation approach needs to be incorporated into the routing and scheduling module with the aim of providing an on-line decision support, the proposed approach in Section III may not be competent for this purpose due to high running time. In light of this, a heuristic procedure was devised in [40]. This heuristic is based on the following observations which were noted during the initial experiments using PAIA as a solution method for the optimal speed profile generation problem:

1) Aircraft mostly accelerate with the maximum acceleration rate $a_{max} = 0.98 \text{ m} \cdot \text{s}^{-2}$ in order to minimise the acceleration time.
2) Fuel consumption during braking is comparable with fuel burn during the constant speed, mostly for the method based on ICAO emissions database.

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 calculated in a pre-processing step. The first observation implies that the decision variable a_1 is fixed to 0.98 m·s⁻². The second observation will maximise the distance d_2 during which the aircraft travels at constant speed v_1, since braking will not save fuel, but will increase traversing time. With maximised d_2 the rapid braking distance d_4 using deceleration $a_{max} = 0.98$m·s⁻² to slow down from v_1 to v_4 can be easily calculated using the following equation:

$$d_4 = \frac{v_1^2 - v_4^2}{2a_{max}}. \tag{32}$$

The only decision variable left undecided is the acceleration distance d_1 which affects the maximum speed v_1 that can be achieved over the segment. The maximum speed v_1 affects the fuel consumption as well as the time needed to traverse the segment. Then, the remaining task is to search for the optimal values of v_1 and hence d_1.

A. Solution Method

The search for a trade-off is performed as described by Fig.11. The heuristic approach starts by iteratively generating speed profiles for each segment seg_n of the route with the maximum speed v_1 set to a value from $v_1 = 5.14$ m·s⁻¹ (10 knots) to $v_1 = 15.43$ 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 u_1 and u_2 is constructed as a set of best

selected speed profiles for all segments (line 13).

```
1:    For all seg_n in route do:
2:        p = 0;
3:        For v_1 = v_turn to v_straight step 1 m·s^-1 do:
4:            Generate speed profile with v_1;
5:            p = p + 1;
6:        End
7:    End
8:    For weight u_1 = 0 to 1 step 1/p do:
9:        u_2 = 1 - u_1;
10:       For all seg_n in route do:
11:           Assign utility u_1 · g_1 + u_2 · g_2 to every speed
              profile generated in line 4;
12:           Select speed profile with the minimum utility;
13:           Assign a_1, d_1, d_2, d_4 to complete solution for
              the whole route;
14:       End
15:   End
```

Fig. 11. Heuristic for speed profile optimisation.

B. Results

The Pareto fronts obtained by the heuristic approach for respective fuel consumption modelling methods are shown in Fig. 12.
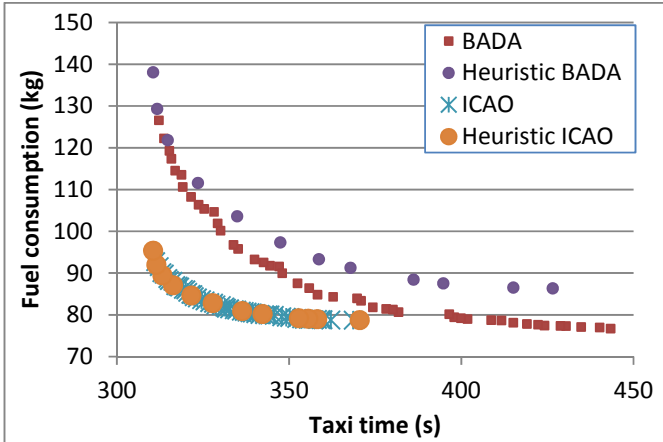

Fig. 12. Pareto fronts of optimal speed profiles generated by the heuristic for two fuel consumption modelling methods.

For the method based on ICAO emissions database, the performances of both the heuristic approach and PAIA are similar. For BADA, the heuristic approach approximated the Pareto front. However, it failed to obtain solutions with low fuel consumption compared with solutions produced by PAIA. This can be explained by the fact that the second observation does not hold for BADA. In fact, in the case of BADA, the fuel flow $f_{3,4} = 0.15$ kg/s during braking is lower than fuel flow $f_2 = 0.19$ kg/s during constant speed.

Although the heuristic approach does not outperform PAIA, the benefit of using this approach lies in computational time. As there is only one decision variable d_1 involved in the search process, and most of other variables are calculated analytically in beforehand, the search space has been greatly reduced, and

hence the Running Time (R.T.) < 1 s. R.T. was significantly shorter compared to PAIA (282 s for the method based ICAO and 525 s for BADA), which makes it suitable for incorporation into routing and scheduling module able to provide decision support in real-time. Fig. 13 shows solutions with $g_1 = 330$ s generated by the heuristic approach using ICAO and BADA. Again, the generated optimal speed profiles based on ICAO and BADA are very similar for the heuristic approach due to the same reasons discussed in Section IV.C. The property of such conformance makes the heuristic approach also valid for routing and scheduling approach even without accurate fuel burn estimation model.
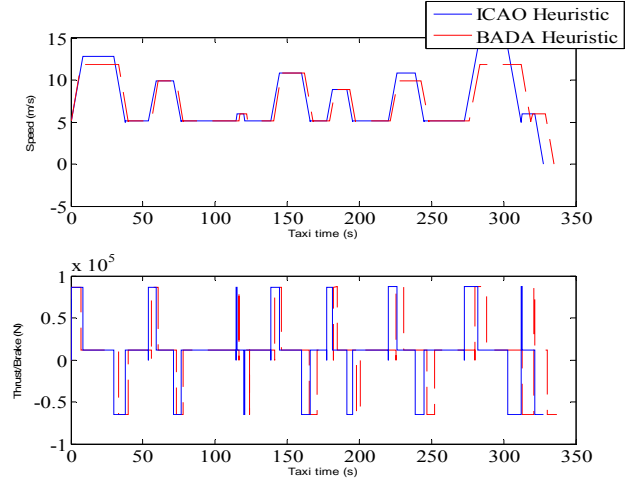

Fig. 13. Speed profiles generated by the heuristic around g_1=330 s for two fuel consumption calculation methods.

VI. CONCLUSIONS

In this paper, a systematic multi-objective optimal speed profile generation framework is introduced in order to generate a set of unimpeded optimal speed profiles along a given route. It is intentional to keep the interaction with other aircraft outside of the proposed framework so that the complex airport ground movement problem remains tractable, especially within the context where many conflicting objectives have to be considered at the same time. The benefits of introducing an evolutionary multi-objective optimisation into this work lie in:

1) Not only can time efficiency be considered like conventional routing and scheduling approach, but also other objectives, such as environmental impact, passenger experience, and pilot behavior, *etc.*, can now all be explicitly and systematically addressed for airport ground movement.

2) As a set of Pareto-optimal unimpeded solutions are available for each aircraft on the given route, routing and scheduling module will have more chances to select feasible solutions and may be able to set up the time constraints for critical nodes of the entire taxiway network based on the most suitable and feasible solution, in order to avoid conflict and maintain safe separation. This is envisioned to be more realistic and efficient as planning is now based on the specific optimal speed profile pertaining to each segment.

It is argued that the optimal speed profile problem modelled in this paper is insensitive to different fuel consumption models. Therefore, given the current situation that no credible ground fuel burn models are available, it is still valid to incorporate the proposed approaches in the routing and scheduling function. The results also suggest that for the design of aircraft engine, a lower fuel flow in the constant speed corresponding to the idle thrust may be beneficial. This will provide more operational benefit. A coherent consideration from both strategic and technical levels for aircraft engine design may further reduce fuel consumption without sacrificing aircraft performance in other phases. For the simplified speed profile problem modelled in this paper, a heuristic approach will be favored due to its on-line decision making capability. As discussed in Part 2 of this paper, the optimal speed profile generation approach is a key element of the Active Routing concept. Furthermore, optimal speed profiles generated using the realistic aircraft motion model increase feasibility of the planning function, as it is easier for pilots to follow.

For future improvement of the proposed method, firstly, a more accurate fuel consumption modelling should be investigated in order to better understand the real saving in fuel burn. Secondly, more precise modelling of jet engine could improve the accuracy of the proposed method by taking into account response to control signals and time to spool up/down. Finally, more accurate aircraft motion model combined with pilot simulator may yield interesting results by considering pilots' behaviours within the optimization procedure, and will facilitate research into non-linear continuous optimal speed profile generation.

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