# The Airport Ground Movement Problem: Past and Current Research and Future Directions

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***Abstract*—Determining efficient airport operations is an important and critical problem for airports, airlines, passengers and other stakeholders. Moreover, it is likely to become even more so given the traffic increases which are expected over the next few years. The ground movement problem forms the link between other airside problems, such as arrival sequencing, departure sequencing and gate/stand allocation. This paper provides an overview, categorisation and critical examination of the previous research for ground movement and highlights various important open areas of research. Of particular importance is the question of the integration of various airport operations and their relationships which are considered in this paper.**

***Index Terms*—Airside airport operations, ground movement, taxiing, survey, future work, integration of airport operations.**

## I. INTRODUCTION

There has been a significant increase in air traffic over the past few years and this trend is predicted to continue. The SESAR (Single European Sky ATM Research) project predicts a doubling in the number of flights between 2005 and 2020 [1]. The project aims to triple capacity by 2020 and to reduce delays on the ground and in the air [2]. It is apparent that the hub airports often form bottlenecks for the overall air traffic management system within Europe. Hence, improvements in critical airport operations will be more and more important in the near future. The main operations which affect this bottleneck are arrival and departure management (sequencing and scheduling) at the runway [3]–[7], gate assignment [8], and ground movement.

The majority of the existing research has focussed on the optimisation of a single airport operation at a time. However, from both an economic point of view (reducing delays and increasing throughput), and an environmental point of view (reducing noise, air pollution and carbon emissions), there are obvious benefits to be gained from treating the different airport operations as a whole.

Ground movement links the various other operations together, and is the focus of this paper which provides, for the first time, a survey and comparison of the existing optimisation approaches within this field. Our purpose is to pinpoint the important open areas, of which, integrating the different airport operations is perhaps the most important potential future research direction.

The remainder of this paper is structured as follows: Section II provides a description of the airport ground movement problem and relates it to the other relevant airport operations. Next, the existing models and solution approaches are discussed and categorised in Section III. We then highlight various important future research directions in Section IV, before ending the paper in Section V with some conclusions.

## II. PROBLEM DESCRIPTION

The airport ground movement problem is basically a routing and scheduling problem. It involves directing aircraft to their destinations in a timely manner, with the aim being to either reduce the overall travel time and/or to meet some target time windows. Throughout the movement, it is crucial for reasons of safety, that two aircraft never conflict with each other. The complexity of the problem can vary and should drive the choice of solution approach. When an airport has only a few aircraft moving at once, with few potential conflicts between them, optimal routing can be achieved by simply applying a shortest path algorithm, such as Dijkstra's algorithm [9], [10], to each aircraft in turn. For larger airports, especially during peak hours, the interaction between the routes of different aircraft often requires the application of a more complex simultaneous routing algorithm.

The details of the problem descriptions and the constraints which have been utilised in previous work have varied according to the requirements of the airport which was being modelled. The various constraints upon the ground movement problem are considered in Section II-A. Since it is important for improving the operations at an airport to integrate the related operations with the ground movement problem, this integration is discussed in Section II-B, after which, the different objectives are described in Section II-C.

### A. Constraints

The different constraints upon the problems discussed in the existing ground movement research literature can be divided into the following categories:

*1) Consideration of the route taken:* It is important to ensure that aircraft follow a permitted route. If the route for each aircraft is pre-determined, the ground movement problem is reduced to finding the best possible schedule [11], [12]. The other extreme occurs when no restrictions are set for the

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routing of each aircraft [13]–[16]. The last possibility is for the restrictions to lie somewhere in between these extremes, where there is a predefined set of routes for each aircraft and the algorithm can choose amongst them [17]–[26].

*2) Separation constraints between aircraft:* As previously mentioned, it is crucial that aircraft do not conflict with each other and have a separation based on jet blast. This is ensured during taxiing by applying separation constraints. The required minimum distances between aircraft appear to vary between authors. For example, Pesic et al. required it to be at least 60 metres [17], while Smeltink et al. required a value of 200 metres [11]. Such constraints can also depend upon the aircraft type or size. If an aircraft is at a gate, no such restriction is usually used. At the point of take-off or landing, other restrictions are employed, which are presented in Section II-B.

*3) Aircraft movement speeds:* Different aircraft require different lengths of time for taxiing. Recent research has taken this into account, modelling the speed depending either upon the type or size of an aircraft [23], [24], or the kind of taxiway that is being followed [18]. The time for making a turn can also be taken into account [17].

*4) Timing constraints for arrivals:* Arriving aircraft have to be routed from the runway to their stands. From the point of view of the isolated ground movement problem, the arrival time for aircraft can be considered to either be fixed or to permit small deviations. The allocated gate is usually assumed to be vacant and, therefore, the aim is usually for the aircraft to reach the gate as soon as possible, since this is better from an environmental as well as an airline and passenger perspective.

*5) Timing constraints for departures:* Departing aircraft have to be routed and scheduled from their stands to the runway from which they will be departing. A pushback time (or earliest pushback time) is usually provided and is often seen as an earliest time for an aircraft to start taxiing. The aims for the ground movement of the departing aircraft can be more complicated than for arrivals. Assuming that the departure sequencing has not been integrated into the problem, one of the following aims is usually adopted: 1) To reach the runway as early as possible. 2) To reach the runway in time to attain, or be as close as possible to, a pre-determined take-off time. 3) To reach the runway in time to take off within a specified time window, since many European aircraft have fifteen minute slots which are allocated by the Eurocontrol Central Flow Management Unit (CFMU) and have to be satisfied [20].

### *B. Integration of other airport operations*

The ground movement problem does not actually occur in isolation at an airport. The arrival sequence will determine the times at which some aircraft enter the system, the gate/stand allocation problem will determine where they leave the system and where departures enter the system. The departure sequencing problem determines the times at which departures leave the system. These systems can be seen to be intimately linked, so potential benefits from integrating all four problems are obvious. However, little research so far has considered this integration. The complexity of these problems is such that it is currently impossible to simultaneously optimise all of these airport operations, but the real situation at the airport means that there has to be at least some coordination between the solutions of the sub-problems.

*1) Integration of departure sequences:* For departing aircraft, the ground movement can affect the departure sequencing, and vice versa. An optimal take-off sequence is of no use if it cannot be achieved by the taxiing aircraft, as discussed in [6]. To maximise the throughput of a runway, two sequence-dependent separations are of major importance [27]: wake vortex separations and en-route separations. The wake vortex separations depend upon the weight classes of the aircraft, so that larger separations are required whenever a lighter class of aircraft follows a heavier class. Separations also have to be increased when aircraft have similar departure routes (to ensure that en-route separations are met) or when the following aircraft is faster (to allow for convergence in the air).

Departure sequencing is sometimes considered within ground movement research [18], especially the newer research [12], [15], [16], [25], [26], in order to ensure that aircraft arrive at the departure runway at appropriate times, rather than merely reducing the overall taxi times. Only wake vortex separations are usually considered. However, the en-route separations are also sometimes taken into account [15], [16].

Similarly, taxi times cannot be ignored in realistic departure sequencing systems. The movement near the runway is especially important, for example, within flexible holding areas [3], [6], or the interleaving of runway queues [28]. Even where the models for movement are not explicitly required, accurate taxi time predictions are often beneficial for improving sequencing [29], even when re-sequencing is performed at the runway, and would be even more important if the re-sequencing was performed earlier.

*2) Integration of arrival sequences:* Aircraft enter the ground movement system by landing on a runway, or by leaving stands. The entry times into the system of landing aircraft will influence the ground movement operations. Better arrival time predictions can have a positive effect on the ground movement planning. There may be a choice of landing runway to be made. This choice can depend upon the current status of the ground movement and the assigned gate for the aircraft. After landing it will influence the later ground movement planning.

In some airport layouts, runway crossings may be necessary for taxiing aircraft. For realistic runway sequencing and taxiing optimisation, such crossings may need to be taken into account [4], requiring knowledge of the runway sequencing when planning the ground movement. Furthermore, runways are sometimes used in mixed mode, in which case departure and arrival sequences also have to be coordinated [5], [7].

*3) Integration of gate assignment:* Gate assignment is another major problem which arises at congested airports. The aim is to find an assignment of aircraft to gates at terminals, or stands on the apron, so that some measure of quality, such as total passenger walking distance, is improved. This problem was fully discussed in a recent survey paper by Dorndorf et al. [8], where the need for future work in multi-objective optimisation and robust assignments was also identified. The ground movement problem could be integrated with the gate assignment problem, with the aim being to allocate gates/stands so that the total taxiing distance is reduced. This would have a beneficial impact upon the use of fuel, with consequent benefits for the environment as well as financial savings for airlines, delay benefits for passengers and a reduction in congestion on the apron.

### C. *Objective functions*

The aim of the ground movement problem depends upon the scope of the problem. Much of the previous research has concentrated upon minimising the total taxi time including the waiting time for aircraft at the runway [12], [13], [17], [24], while other research has considered makespan (the duration from first to last movement) minimisation [21], [22]. Yet more research has treated this as a multi-objective problem. For example, penalising deviations from a scheduled time of departure/arrival (STD/STA) [11], [23], [25], [26], or from the CFMU slots [20], in addition to considering one of the total taxi time or makespan reduction objectives. In other research, longer taxi paths were penalised as well [15], [16], [18]. Marín and Codina [14] used a weighted linear objective function to simultaneously consider the total routing time, number of controller interventions, worst routing time, delays for arriving and departing aircraft and the number of arrivals and take-offs.

### D. *Related research areas*

Similar problems have been considered in other areas of research, such as the control of Automated Guided Vehicles (AGVs) [30], job-shop scheduling with blocking [31], train routing and scheduling [32] and airport surface conflict detection and resolution [33]. Of course, the details of the constraints and objectives differ, so there are limits to the applicability of the research.

## III. EXISTING MODELS AND SOLUTION APPROACHES

In this section, we present a comparison and categorisation of the existing research for the ground movement problem at airports, which has previously taken two forms. The first form has involved the development of a Mixed Integer Linear Programming (MILP) formulation, to which a commercial solver was usually applied, yielding an optimal solution. Where models were formulated in a manner which would not be tractable to a MILP solver within a reasonable solution time, heuristic methods have been applied. This alternative approach has so far exclusively involved the use of Genetic Algorithms (GAs). Of course, as heuristics, GAs give no guarantee of the optimality of the solutions found. However, their success over far shorter (and far more realistic in practice) execution times can sometimes more than compensate for this.

We will first focus on the MILP formulations before discussing the GA-based approaches. For each approach, we will first discuss the various models which have been developed, before considering the previous research which has used these models in more depth. We will then compare the approaches, discussing the advantages and disadvantages of each. Finally, we end this section by considering two important issues: firstly, how do the models handle the dynamic nature of the real problems at the airports, and secondly, how can speed uncertainty be handled to make the solution more robust in the real situation? An overview of the published ground movement optimisation research considered here can be found in Table I, showing in chronological order both the solution approach which has been adopted and the defining characteristics of the model.

TABLE I
OVERVIEW OF APPROACHES FOR THE GROUND MOVEMENT PROBLEM

| Authors | Year | Approach | Representation |
|---|---|---|---|
| Pesic et al. [17] | 2001 | GA | Times |
| Gotteland et al. [18], [19] | 2001/3 | GA | Ordering, Times |
| Gotteland et al. [20] | 2003 | GA | Ordering |
| Smeltink et al. [11] | 2004 | MILP | Ordering |
| García et al. [21], [22] | 2005 | GA | Times |
| Marín [13] | 2006 | MILP | Times |
| Balakrishnan and Jung [23] | 2007 | MILP | Times |
| Marín and Codina [14] | 2008 | MILP | Times |
| Roling and Visser [24] | 2008 | MILP | Times |
| Deau et al. [25], [26] | 2008/9 | GA | Ordering |
| Keith and Richards [15] | 2008 | MILP | Ordering |
| Rathinam et al. [12] | 2008 | MILP | Ordering |
| Clare and Richards [16] | 2009 | MILP | Ordering |

### A. *Mixed integer linear programming (MILP) formulations*

MILP formulations are widely used by exact solution methods in operational research. In comparison to Linear Programming (LP) formulations where the objective function and constraints all have to be linear, MILP formulations introduce an additional restriction of integrality for some variables. Unfortunately, since this restriction changes the nature of the search space from continuous to discrete, it often leads to problems which are much harder to solve, so that solution times for large problems may no longer be practical.

Three different MILP modelling approaches, which have been adopted, are described below:

- Exact position approach: Here a time is allocated for each aircraft to traverse each individual part of its path. The approaches of Marín [13], Balakrishnan and Jung [23], Marín and Codina [14] and Roling and Visser [24] used a space-time network for this purpose. A spacial network representing the map of the airport is used as a starting point, then time is discretised and a copy of the underling spacial network is created for each time unit. These are then used to build a time expanded network. A good illustration of this can be found in Marín and Codina [14].
- Ordering approach: In this case, rather than dealing directly with timings, the algorithm first aims to decide upon the sequencing, then uses this information to schedule times for each aircraft at each node or edge.

This approach was adopted by Smeltink et al. [11], Rathinam et al. [12], Keith and Richards [15] and Clare and Richards [16]. All of these only required a spacial network and modelled the sequencing constraints using binary variables, where the variables for a pair ($i$,$j$) of aircraft at a node/edge are equal to one if and only if aircraft $i$ passes this node/edge before aircraft $j$. With this approach, the times for each aircraft can be modelled as continuous variables, avoiding the disadvantages of time discretisation.

- Immediate predecessor/successor approach: It would also be possible to indicate only the immediate predecessor and successor for each aircraft at each node/edge rather than a full sequencing. As far as we can determine, this approach has not been used for solving the ground movement problem so far. Although the model in Smeltink et al. [11] indicated the immediate predecessor aircraft, this was only to support the ordering model.

### *B. Review of previous MILP-related research*

To our knowledge, Smeltink et al. [11] was the first approach to handle the ground movement problem using the MILP formulation. This was performed for Amsterdam Schiphol Airport in 2004. Since this airport used standard, predefined taxi routes for aircraft, the problem was reduced to a scheduling problem. The approach worked on a spacial network where times were modelled as continuous variables and binary variables were used for the sequencing, as described above. The objective was to minimise the waiting time while taxiing and the deviation between the desired departure time and the scheduled departure time.

In 2006, Marín [13] presented a linear multi-commodity flow network model to simultaneously solve the aircraft routing and scheduling problem around airports. Two different methodologies were used to solve the MILP formulation: a branch and bound, and a fix and relax approach. In the latter case, the planning period was split into $k$ smaller periods. Initially, only the variables within the first time period are taken as binary and a linear relaxation is applied to the variables for the other periods. The variables for the first period are then fixed, the variables for the second time period are made binary and the linear relaxation is maintained for the remaining variables. This is repeated for all $k$ periods until all of the variables have been fixed. The objective of the MILP formulation was to minimise the total taxi time.

Marín and Codina later published further work [14] where the model was multi-objective. The weighted linear objective function considered five other objectives, in addition to the previous goal of reducing the total routing time: 1) reducing the number of controller interventions, 2) reducing the worst routing time, 3) reducing the delays for arrivals, 4) reducing the delay for departures and 5) attempting to maximise the number of arrivals and take-offs. In contrast to other models, they allowed the aircraft to use the whole network and did not restrict them to a pre-determined set of paths. However, the presented algorithm was not able to deal with the separation constraints in an accurate way because the constraints were only modelled in the space-time network, which is independent of the type or size of aircraft.

Balakrishnan and Jung [23] published another MILP formulation of the ground movement problem on a space-time network. In this approach, each aircraft could be allocated one of a limited set of routes. The relative benefits of different control approaches, such as controlled pushback and taxi path re-routing were also considered. Their aim was to minimise the total taxi time and to penalise situations where aircraft departed too late. It was pointed out that controlled pushback could reduce the average departure taxi time significantly, saving fuel.

An alternative MILP formulation for ground movement, which was also based on a space-time network, was provided by Roling and Visser [24]. A number of alternative routes were assigned to each aircraft beforehand, and only these were considered at the solution stage. It was possible for an aircraft to wait at the beginning of the journey, as well as on special nodes during the journey. The objective was to minimise a weighted combination of the total taxi time and total holding time at the gates. The objective function considered the entire route for each aircraft but the solution was only guaranteed to be conflict-free within the planning horizon, since these constraints were relaxed for later times.

Rathinam et al. [12] used a MILP formulation which was based on the work of Smeltink et al. [11] and primarily considered the ordering of the aircraft at nodes. Further separation constraints were added to the model, and it was simplified by reducing the number of binary variables. The algorithm used a spacial network and a predefined route for each aircraft, to minimise the total taxi time.

Keith and Richards [15] introduced a new model for the coupled problem of airport ground movement and runway scheduling. Their MILP optimisation was influenced by the work of both Smeltink et al. [11] and Marín [13]. The objective function was a weighted combination of minimising the makespan, the total taxi and waiting time and the total taxi distance. As in Smeltink et al. [11], a spacial network was used, with binary variables for handling the sequencing constraints and continuous variables for the timings. Although both wake vortex and en-route separations were considered for the take-off sequencing element, there were no route limitations applied. The work of Clare (nee Keith) and Richards [16] extended their previous work. Their MILP formulation was changed to make it possible to introduce an iterative solution method. In the first step, a relaxed MILP formulation was solved, and no guarantees were given for a conflict-free solution. An iterative procedure was then applied, where additional constraints were added where they were necessary to avoid any conflicts detected in the previous iteration. This was repeated until a conflict-free schedule was found.

### *C. Genetic algorithm (GA) models*

GAs are search methods inspired by evolutionary biology. They incorporate the ideas of natural selection, mutation and crossover [34]. GAs maintain a population of candidate solutions, have a method (called a fitness function) for evaluating solutions and apply a selection mechanism to guide the algorithm towards good solutions. The correct encoding of the problem can be key for the successful application of a GA (as we will consider in the next section), as can be the choice of appropriate mutation and crossover operators for the selected problem encoding.

We now consider the important elements of the encodings which have been used for the ground movement problem over the last decade before considering, in Section III-D, the specific encodings. As for the MILP approaches, the GAs consider either the absolute timing or the relative sequencing of the ground movement.

All of the encodings which have been considered in the GA implementations, [17]–[22], [25], [26], included the route allocation information, specifying the route $r_i$ to allocate for each aircraft $i$. The additional information which was included differed between the approaches, but can be summarised into three categories:

- Applying an initial (aircraft-specific) delay/hold time, prior to pushback. The GA is responsible for determining this delay for each aircraft, as well as the route to allocate. This approach was adopted by [21], [22].
- Applying a delay at some point during the movement, and not restricting it to being applied at the start of the taxiing. This could be implemented either by specifying times for both initiating and terminating the delay (the approach which was adopted in [17], [19]) or as a delay amount and (spacial) position at which to apply it to the aircraft, as in [18]. The GA is responsible for investigating when or where to apply the delay and the duration or end time of the delay as well as the route to allocate to the aircraft.
- Prioritising aircraft movement, where the GA is used to investigate the relative prioritisation of the aircraft rather than allocating holds directly. Here, the priority determines which aircraft take precedence when there are conflicts during the movement. This approach was adopted in [18]–[20], [26], where the GA investigated the priorities to assign to aircraft as well as the routes.

### D. *Review of previous GA-related research*

As far as we can determine, Pesic et al. [17] published the first paper for optimising the ground movement problem at airports in 2001. They allowed a single delay per aircraft at a time determined by the GA. Their fitness function considered the number of time steps $C$, for which aircraft were in conflict during the movement, and the total travel time $T$ for aircraft. The GA aimed to maximise the fitness value, which was $\frac{1}{2+C}$ in the presence of conflicts or $\frac{1}{2}+\frac{1}{T}$ in the absence of conflicts. All values bigger than $\frac{1}{2}$ corresponded to solutions which were conflict-free and all values smaller than $\frac{1}{2}$ had at least one conflict and were therefore infeasible. Crossover and mutation operators were introduced along with a diversification strategy and some simple termination criteria. For a random pair of parent solutions, the crossover operator chose for each aircraft the parent which had fewer conflicts with other aircraft, in order to increase the probability of producing an offspring population with better fitness values. This operator was appropriate because the problem was partially separable [35]. The mutation modified the details for the aircraft with the (potentially shared) worst local fitness value.

Gotteland et al. [18] extended their previous work by considering how the GA could deal with speed uncertainty. We believe that this is an important consideration and will discuss it in Section III-G. In addition to the encoding from their previous work [17], they used a representation for prioritising aircraft movements, discussed in Section III-C. The encoding included the route number and priority level for each aircraft. A fitness value was computed by applying an A* algorithm with the specified prioritisation of the aircraft. A space-time network was then generated and aircraft were routed in order of priority level. After an aircraft had been routed, the network was adjusted in such a way that the allocated route was removed, along with all potentially conflicting edges, so that the routing of the next aircraft avoided conflicts with previous aircraft.

The clustering of aircraft within these ground movement problems was considered in [18]. A two stage approach was adopted, where the clusters of aircraft with conflicts were solved independently in the first stage, before the different clusters were unified and solved in combination in the second stage.

Gotteland et al. [19] subsequently presented an alternative sequential algorithm: a branch and bound algorithm, with a first search strategy replacing the A* algorithm to speed up the calculation of the fitness value, since there is always a preference to continue taxiing rather than to hold position.

Gotteland et al. [20] explained the way in which their GA handles both take-off time prediction and CFMU slots. They modified their algorithms from [18] with the aim of reducing the deviation from CFMU slots (rather than minimising the necessary taxiing time) by penalising (with a linear cost) deviations from the desired take-off times for each aircraft, with a steeper penalty when the scheduled take-off is outside the CFMU slot.

García et al. [22] hybridised two earlier approaches which were previously detailed by the same authors in [21]. A modified minimum cost maximum flow algorithm determined the initial population of a GA and was used to penalise the fitness function. The approach considered the application of an initial delay at the gate and the allocation of a route to each departing aircraft, with no possibility for waiting at intermediate points or slower taxiing during the ground movement. They used tournament selection, single-point crossover, a traditional mutation operator and an additional random variation of the delay time. Their fitness function penalised infeasible solutions and tried to minimise the makespan and the sum of the delays, while attempting to maximise the number of departing aircraft.

Two more recent papers from Deau et al. [25], [26], developed the ideas which have been discussed for [17]–[20]. They proposed a two-phase approach which considered the runway sequencing in the first stage and the ground movement in the second stage. The separations to account for the wake vortices were the most important constraint for the runway sequencing element. A deterministic constraint satisfaction problem solution algorithm was used, which was based on a branch and bound methodology. They used an objective function which was similar to that which was used in Gotteland et al. [20]. Departing aircraft were moderately penalised if their scheduled time deviated from the desired time within the CFMU slot, but were much more heavily penalised if the scheduled time was outside this slot. Arriving aircraft had a fixed predicted time to land, so a solution was only feasible if these aircraft had, at most, a small delay (no more than one minute) compared with the predicted landing time. In the second stage, their GA was modified to find a good solution for the ground movement problem given the runway sequencing from the first stage. The target runway sequence was considered as the ideal result of the routing stage, but was not treated as a hard constraint, thus, the fitness function for their GA penalised deviations from the target times.

### E. Comparison of the approaches

We now consider the major differences between the different models and solution approaches.

*1) Differences in objectives and constraints:* The optimisation of airport operations is a real-world problem, and as such it is important that the real objectives of the airport and real constraints upon the problem are considered. The majority of the published work has considered real airport settings, and it is apparent that both the objectives and the details of the constraints have differed between airports. Consequently, the models for the problems have also differed, resulting in the development of different solution approaches.

*2) Optimality vs. execution time:* The solution approach which is adopted may also depend upon the load upon the airport (i.e. the number of aircraft which need to be simultaneously considered), since exact solution approaches become less practical as loads increase. With the expected increases in the density of air traffic meaning that airports have to be able to handle more aircraft in the near future, some solution approaches may potentially need to be adjusted over time.

It is well known that GAs are heuristics rather than exact solution methods and can, therefore, often give neither any guarantee for the solution nor even an approximation ratio in many situations. However, a poor formulation of a MILP can also mean that an exact solution to the MILP can be a poor solution for the underlying real-world problem. For example, with time discretisation models, the way in which the time discretisation is handled can have a major effect upon the optimality of the results: smaller intervals may give better results but will result in significantly larger problems to solve. Similarly, the way in which a model deals with the separation rules between aircraft can affect the quality of the results. It should be noted that none of the papers which were discussed here measured the optimality gap for realistic scenarios, evaluating the effects of utilising only a heuristic (GA-based) solution approach or of the effects of time discretisation, perhaps due to the difficulty or impracticality of optimally solving these problems. In our opinion, it would be worthwhile to have some kind of comparison between the performance of the approaches, to be able to see the trade-off explicitly.

Due to the fact that airports are usually interested in real time decisions, the execution time of an algorithm is a crucial measure. From this point of view, heuristics such as GAs outperform MILP formulations. For example, in [24] it was shown that the execution time increased dramatically as the number of aircraft increased.

Different researchers have also used different objective or fitness functions, due to having slightly different aims. We believe that the generation of some generic benchmark scenarios to allow such an analysis to be performed, comparing exact and heuristic solution approaches and the effects of different objective functions, would be of huge benefit and is a path down which we plan to proceed.

As far as we are aware, there has been no investigation using other metaheuristics such as simulated annealing [36], or tabu search [37]. Furthermore, there seems to be an unexploited potential for hybrid approaches which can make use of the advantages of different models.

### F. Dealing with the dynamics

One major characteristic of the problem of ground movement at airports is the dynamic nature of the problem. Predictions become less accurate the further they are in the future: predicted positions for current aircraft may be wrong as may be predictions of when new aircraft will be ready to pushback from the gates or to land. Predictions, therefore, have to be regularly updated and, since some approaches need a significant execution time, attempts have been made to decompose the problems into smaller sub-problems. In this section, we summarise the approaches which have been used to cope with the dynamic nature of the routing problem.

- A simple modelling approach, by the name of *shifted windows*, was introduced by Pesic et al. [17] for their GA. Every $\Delta$ minutes, the situation was resolved for a fixed time window. Only arriving or departing aircraft within the time window were considered but the time window was enlarged for these aircraft to avoid horizon effect problems.
- Smeltink et al. [11] evaluated three different variants of a *rolling horizon* approach, not only for handling the dynamics of the problem, but also to reduce the size of the problem to be solved. In each case, the planning period was split into disjoint, equal length time intervals. In the first variant, the routes which had been allocated in previous intervals were considered to be fixed, while in the second variant they could be modified. In the third variant, the aircraft were sorted according to their push-back or landing time, respectively, and a *sliding window* was applied to consider $m$ aircraft in each iteration. The first iteration considered aircraft 1 to $m$, then aircraft

1 was fixed and aircraft 2 to $m+1$ were considered, then aircraft 2 was fixed, and so on. Unfortunately, this variant had a significantly higher execution time without increasing the solution quality significantly.
- The fix and relax approach (discussed in Section III-B) which was used by Marín [13] for solving his MILP formulation, worked in a similar way to the sliding window approach. He also used an alternative time-interval-based approach, where only aircraft in a particular interval were used for planning but the interval was not enlarged to guarantee a conflict-free solution. Instead, a shortest path algorithm was used to estimate the remaining time for the aircraft which do not reach their destination within the interval.

### G. Robustness and speed uncertainty

Almost all published approaches were based on deterministic data. However, the real world situation at airports is less predictable. Therefore, we think it is important to take solution robustness into consideration. Uncertainty in the data for the ground movement problem can appear in different areas, one of which is speed predictions. An approach to cope with this was presented and illustrated in Gotteland et al. [18]. They modelled the speed uncertainty as a fixed percentage of the predefined speed. Hence, an aircraft was assumed to occupy not only a single position in the network but multiple possible positions at the same time. While an aircraft was taxiing, the number of occupied positions grew and when an aircraft was waiting at a holding point, the speed uncertainty and number of occupied positions decreased.

## IV. IMPORTANT FUTURE DIRECTIONS

In this section, we describe several important open research directions for the airport ground movement problem.

### A. Consistency and comparability

As discussed in Section III-E, the constraints and objectives vary widely within the published research. No comparison has so far been performed between different approaches, so it is difficult to estimate the gap between the exact optimisation methods (e.g. MILP formulations) and the heuristic approaches (e.g. GA) for either the quality of the solution or the execution time of the algorithms. More consistency is desirable. For this reason, and in an attempt to promote research in this area, we have set up a repository for datasets for these problems[1] and intend to do some quantitative comparison.

### B. Integration of other airport operations

The integration of other airport operations, such as departure and arrival sequencing and gate assignment, is highly desirable and, ultimately, optimisation across multiple airports would be even better. Of course, the complexity of the integrated problem would grow and, since the computation is time-critical, there seems to be more potential for heuristic and hybrid methods than exact approaches. With the integration of different airport operations, the problem may also have to be treated as a multi-objective optimisation problem.

### C. Robustness and uncertainty

Uncertainty in the input data is common at airports. Push-back time uncertainty and taxi speed/duration uncertainty are known to be major limiting factors upon the accuracy of models. We see the need for more investigation into models of the airport ground movement problem which are more robust against such uncertainty.

### D. Restricted stopping positions

It is easier to hold aircraft at some points (for example at lights built into the taxiways) than at others and, in some cases, it is reasonable to hold an aircraft in a specific position only under certain circumstances. For example, it is reasonable to ask a pilot to wait in a queue behind another aircraft, but may not be sensible to request a pilot to 'taxi until 12:05 then pause for 30 seconds'. Different modelling and solution approaches can result in different operational modes. We suggest that the approach to adopt should be influenced by the real operating modes, so that the algorithmic results can correspond to instructions which could be given to pilots, ensuring that plans could actually be enacted.

### E. Environmental considerations in taxiing

Consideration of the environmental effects of airports has become increasingly important and could be taken into account for ground movement. For example, where possible, delays for an aircraft should be scheduled prior to starting the engines, i.e. as initial delays at the gate/stand.

Perhaps more interestingly from the point of view of the problem modelling, aircraft engines are more efficient when a constant taxi speed can be maintained rather than having a lot of acceleration and deceleration. Speed changes and multiple stops should, therefore, be avoided or reduced. It may be advisable to consider some kind of post-processing to calculate speeds for link traversals, so that the pilots could be given appropriate information to allow them to replace higher speed taxi operations plus waits by a lower speed operation.

### F. Limiting changes

When the real-world dynamic case is considered, it is possible that routes or sequencing can change over time. This may be highly undesirable if information has been transmitted to pilots. Thus, the effects of avoiding changes should at least be considered.

## V. CONCLUSIONS

This work provides the first overview and comparison of the various ground movement models and solution methods in the literature. It is apparent that there are significant differences between both the objectives and the constraints which were utilised in previous research. To some degree this is inevitable due to the differences between airports and different stakeholder aims. However, there is obvious benefit

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[1] Some datasets and details are available at http://www.asap.cs.nott.ac.uk/atr/benchmarks/ and we encourage further contributions.

to be gained from a formalisation of these. The state-of-the-art approaches use either a MILP formulation or a genetic algorithm approach and a categorisation of the representations has been provided for both.

In addition to highlighting the state-of-the-art in this research area, a number of interesting and important future research directions have also been identified. Of particular importance is the integration of other (highly-related) airport operation problems. Runway sequencing (for both departures and arrivals) and gate assignment are highly connected to the problem of airport ground movement and we suggest that there would be benefits from handling them simultaneously. More consistency within airport operations would also be helpful and generic benchmark scenarios would be useful for both quantifying algorithms and encouraging further research by those who may not have direct contact with an airport. Finally, we have identified the importance of handling uncertainty in taxi speeds and generating robust solutions and of considering the operational limitations of communicating instructions to pilots and the environmental effects of decisions.

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## REFERENCES

[1] SESAR, "Milestone deliverable D1 - air transport framework: The current situation," Eurocontrol, Tech. Rep. Edition 3, 2006. [Online]. Available: http://www.eurocontrol.int/sesar/public/standard_page/documentation.html

[2] ——, "European air traffic management master plan," Eurocontrol, Tech. Rep. Edition 1, 2009. [Online]. Available: http://www.eurocontrol.int/sesar/public/standard_page/documentation.html

[3] R. A. Leese, A. Craig, R. Ketzscer, S. D. Noble, K. Parrott, J. Preater, R. E. Wilson, and D. A. Wood, "The sequencing of aircraft departures," Study report from the 40th European Study Group with Industry, Tech. Rep., 2001. [Online]. Available: http://www.smithinst.ac.uk/Projects/ESGI40/ESGI40-NATS/Report

[4] I. Anagnostakis and J.-P. Clarke, "Runway operations planning: A two-stage solution methodology," in *Proceedings of the 36th Annual Hawaii International Conference on System Sciences, Los Alamitos, USA*, 2003.

[5] L. Bianco, P. DellOlmo, and S. Giordani, "Scheduling models for air traffic control in terminal areas," *Journal of Scheduling*, vol. 9, pp. 223–253, 2006.

[6] J. A. D. Atkin, E. K. Burke, J. S. Greenwood, and D. Reeson, "Hybrid metaheuristics to aid runway scheduling at London Heathrow airport," *Transportation Science*, vol. 41, no. 1, pp. 90–106, 2007.

[7] D. Böhme, R. Brucherseifer, and L. Christoffels, "Coordinated arrival departure management," in *Proceedings of the 7th USA/Europe Air Traffic Management R&D Seminar, Barcelona, Spain*, 2007.

[8] U. Dorndorf, A. Drexl, Y. Nikulin, and E. Pesch, "Flight gate scheduling: State-of-the-art and recent developments," *Omega*, vol. 35, no. 3, pp. 326–334, 2007.

[9] E. W. Dijkstra, "A note on two problems in connexion with graphs," *Numerische Mathematik*, vol. 1, pp. 269–271, 1959.

[10] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, *Introduction to Algorithms*, 2nd ed. MIT Press and McGraw-Hill, 2001.

[11] J. W. Smeltink, M. J. Soomer, P. R. de Waal, and R. D. van der Mei, "An optimisation model for airport taxi scheduling," in *Proceedings of the INFORMS Annual Meeting, Denver, USA*, 2004.

[12] S. Rathinam, J. Montoya, and Y. Jung, "An optimization model for reducing aircraft taxi times at the Dallas Fort Worth International Airport," in *Proceedings of the 26th International Congress of the Aeronautical Sciences*, 2008.

[13] Á. Marín, "Airport management: Taxi planning," *Annals of Operations Research*, vol. 143, no. 1, pp. 191–202, 2006.

[14] Á. Marín and E. Codina, "Network design: Taxi planning," *Annals of Operations Research*, vol. 157, no. 1, pp. 135–151, 2008.

[15] G. Keith, A. Richards, and S. Sharma, "Optimization of taxiway routing and runway scheduling," in *Proceedings of the AIAA Guidance, Navigation and Control Conference, Honolulu, Hawaii, USA*, 2008.

[16] G. Clare, A. Richards, and S. Sharma, "Receding horizon, iterative optimization of taxiway routing and runway scheduling," in *Proceedings of the AIAA Guidance, Navigation and Control Conference, Chicago, USA*, 2009.

[17] B. Pesic, N. Durand, and J.-M. Alliot, "Aircraft ground traffic optimisation using a genetic algorithm," in *Proceedings of the Genetic and Evolutionary Computation Conference, San Francisco, USA*, 2001.

[18] J.-B. Gotteland, N. Durand, J.-M. Alliot, and E. Page, "Aircraft ground traffic optimization," in *Proceedings of the 4th USA/Europe Air Traffic Management R&D Seminar, Santa Fe, USA*, 2001.

[19] J.-B. Gotteland and N. Durand, "Genetic algorithms applied to airport ground traffic optimization," in *Proceedings of the Congress on Evolutionary Computation, Canberra, Australia*, vol. 1, 2003.

[20] J.-B. Gotteland, N. Durand, and J.-M. Alliot, "Handling CFMU slots in busy airports," in *Proceedings of the 5th USA/Europe Air Traffic Management R&D Seminar, Budepest, Hungary*, 2003.

[21] J. G. Herrero, A. Berlanga, J. M. Molina, and J. R. Casar, "Methods for operations planning in airport decision support systems," *Applied Intelligence*, vol. 22, no. 3, pp. 183–206, 2005.

[22] J. García, A. Berlanga, J. M. Molina, and J. R. Casar, "Optimization of airport ground operations integrating genetic and dynamic flow management algorithms," *AI Communications*, vol. 18, no. 2, pp. 143–164, 2005.

[23] H. Balakrishnan and Y. Jung, "A framework for coordinated surface operations planning at Dallas-Fort Worth International Airport," in *Proceedings of the AIAA Guidance, Navigation, and Control Conference, Hilton Head, USA*, 2007.

[24] P. C. Roling and H. G. Visser, "Optimal airport surface traffic planning using mixed-integer linear programming," *International Journal of Aerospace Engineering*, vol. 2008, no. 1, pp. 1–11, 2008.

[25] R. Deau, J.-B. Gotteland, and N. Durand, "Runways sequences and ground traffic optimisation," in *Proceedings of the 3nd International Conference on Research in Air Transportation, Fairfax, USA*, 2008.

[26] ——, "Airport surface management and runways scheduling," in *Proceedings of the 8th USA/Europe Air Traffic Management R&D Seminar, Napa, USA*, 2009.

[27] J. Atkin, "On-line decision support for take-off runway scheduling at London Heathrow airport," PhD Thesis, The University of Nottingham, 2008.

[28] M. A. Bolender, "Scheduling and control strategies for the departure problem in air traffic control," Ph.D. dissertation, University of Cincinnati, 2000.

[29] J. A. Atkin, E. K. Burke, J. S. Greenwood, and D. Reeson, "On-line decision support for take-off runway scheduling with uncertain taxi times at London Heathrow airport," *Journal of Scheduling*, vol. 11, no. 5, pp. 323–346, 2008.

[30] I. F. Vis, "Survey of research in the design and control of automated guided vehicle systems," *European Journal of Operational Research*, vol. 170, no. 3, pp. 677–709, 2006.

[31] N. G. Hall and C. Sriskandarajah, "A survey of machine scheduling problems with blocking and no-wait in process," *Operations Research*, vol. 44, no. 3, pp. 510–525, 1996.

[32] J.-F. Cordeau, P. Toth, and D. Vigo, "A survey of optimization models for train routing and scheduling," *Transportation Science*, vol. 32, no. 4, pp. 380–404, 1998.

[33] J. García, J. A. Besada, G. de Miguel, and J. Portillo, "Data processing techniques for conflict detection on airport surface," in *Proceedings of the 5th USA/Europe ATM R&D Seminar, Budepest, Hungary*, 2003.

[34] K. Sastry, D. Goldberg, and K. Graham, *Search Methodologies*. Springer, 2005, ch. Genetic Algorithms, pp. 97–125.

[35] N. Durand and J.-M. Alliot, "Genetic crossover operator for partially separable functions," in *Proceedings of the third annual Genetic Programming Conference, USA*, 1998.

[36] E. Aarts, J. Korst, and W. Michiels, *Search Methodologies*. Springer, 2005, ch. Simulated Annealing, pp. 187–210.

[37] M. Gendreau and J.-Y. Potvin, *Search Methodologies*. Springer, 2005, ch. Tabu Search, pp. 165–186.