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Coordination of scheduling decisions in the management of airport airspace and taxiway operations

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ABSTRACT

This paper addresses the real-time problem of coordinating aircraft ground and air operations in an airport area. At a congested airport, airborne decisions are related to take-off and landing operations, while ground (taxiway) decisions consist of scheduling aircraft movements between the gates and the runways. Since the runways are the initial/terminal points of both decisions, coordinated actions have a great potential to improve the overall performance. However, in the traffic control practice the different decisions are taken by different controllers, at least in large airports. Weak coordination may result in long queues at the runways, with increasing aircraft delays and energy consumption. This paper investigates models, methods and policies for improving the coordination between taxiway scheduling and airborne scheduling. The performance of a solution is measured in terms of delay and travel time, the latter being related to the energy consumption of an aircraft. A microscopic mathematical formulation is adopted to achieve reliable solutions. Exact and heuristic methods have been analysed in combination with the different policies, based on practical-size instances from Amsterdam Schiphol airport, in the Netherlands. Computational experience shows that good quality solutions can be found within limited time, compatible with real-time operations.

Keywords: Air Traffic Control; Scheduling Policies; Ground Operations; Intelligent Decision Support; Schedule Optimization; Alternative Graph

1. Introduction

To a large extent, the real-time management of airport operations is still based on the decisions of human traffic controllers, who develop feasible aircraft schedules in each airport based on their past experience, intuition and some scheduling rules. Recently though, initiatives like the Airport Collaborative Decision Making (A-CDM) of SESAR program [18, 21, 30, 37] are pushing airports towards the adoption of at least automated advisory systems for some of the airport operations. The annual report 2016 [19] of the U.S. Federal Aviation Administration (FAA) cites, among the potential benefits of sophisticated scheduling software, (1) the mitigation of the safety risks associated with controller fatigue; (2) the improvement of the ability of diverse facilities to generate efficient schedules; (3) the possibility of development of staffing standards at FAA headquarters and the creation of work schedules at the facility level. Some commercial arrival manager systems are in operation at some airports [22, 40]. However, with these systems, controllers usually have to manually adjust the aircraft sequencing produced automatically, since the existing systems do not fully take into account the microscopic detail of the aircraft movement required to ensure feasible landing and take-off schedules. These systems usually take decisions based on local and partial information on airport management, while optimization is often limited to very simple scheduling rules. Furthermore, the management of a Terminal Control Area (TCA) requires to coordinate a number of operations (e.g., ground and/or air traffic) that are under the control of different authorities (e.g., the Terminal Radar Approach Control, or TRACON, the Ground Control and the Tower Control [20]). Hence, the overall plan of operations must take into account the different needs and points of view of the various stakeholders [37]. As a result, even when some decisions are supported by advisory systems, a significant part of the controller workload consists of manually coordinating arrivals, departures and other operations to ensure the global feasibility of the overall schedule [17]. Diffenderfer et al. [16] report on the current need of adding the computation of arrival and departure schedules to the functionalities of the systems dedicated to the support of traffic controllers, pointing out that main limitations of the current practice are related to a lack of precision in modeling safety separations between consecutive aircraft and a lack of coordination between arrival and departure operations. These limitations may cause the generation of inefficient schedules in practice. The authors identify the manual communication between controllers as a cause of the slow and inefficient process of coordinating the schedules produced by the Tower Control and by the TRACON, and clearly show that a better coordination of traffic flows might significantly improve the airport performance. However, they do not report nor propose existing methods to this aim.

From the above discussion, it follows that a prerequisite for the introduction of advanced scheduling systems is the development of optimization models and methods that should be able to:

- Incorporate an increasing level of realism, to ensure the schedule feasibility in practice;

- Include the different operations having an impact on performance indicators, or at least address the coordination of different traffic control authorities;

- Support different performance indicators and/or scheduling policies. A scheduling policy prescribes the distribution of slack time for the aircraft besides their minimum traversing time, e.g., at the gate or along the taxiway for take-off aircraft, or before/after entering the TCA for landing aircraft.

So far, the aircraft scheduling literature mainly addressed the first challenge. An extensive overview of early contributions can be found in Ball et al. [7], while more recent surveys can be found in [8, 9, 30]. We observe that, while the coordination issue is often referred to multi-airport coordination, as in [1, 2, 7, 8, 21], this paper focuses on coordination of operations in a single airport. Various approaches have been proposed for the runway scheduling [6, 39], as well as for the landing scheduling from airspace resources to runways [3, 23, 24, 25], or on the coordination of the TCA airspace and the runways (landing and take-off scheduling) [10, 13, 14, 26, 29, 32, 33, 34, 35, 36]. Other papers focus on ground control (including taxiway resources and runways) [4, 5, 11, 27, 31]. Overall, most of the optimization models proposed in the literature for a single control area suffer from a lack of coordination between air and ground operations, so that the solutions produced are not always feasible when implemented in practice. This lack of research motivates the present paper.

This paper focuses on the overall Aircraft Scheduling Problem (ASP) faced by three different authorities: the Approach Radar Control, the Ground Control and the Tower Control [20]. The ASP consists of scheduling aircraft from the border of the TCA until the gate and *vice versa*, by integrating taxiway, landing and take-off scheduling into a single optimization model. We consider the gate assignment problem as solved beforehand, and formulate the overall scheduling problem as a job shop scheduling problem with additional constraints, following a successful stream of research described in Bennell et al. [9]. Along this stream of research, optimization models tend to incorporate an increasing number of details of the practical problem that affect the feasibility of the solutions. Models in this stream, that we call *microscopic optimization models,* have been proposed in [10, 13, 14, 32, 33, 34, 35, 36] for the ASP limited to air resources and runways. Bianco et al. [10] propose a no-wait version of the job shop scheduling problem to model airborne aircraft movements. The latter six papers are based on the alternative graph model introduced by Mascis and Pacciarelli [28], that is able to model aircraft movements with an increased level of detail. The higher modelling precision includes further relevant TCA aspects such as holding circles, waiting in flight before landing, traveling in feasible time windows, hosting multiple aircraft simultaneously in air segments and the single blocking capacity of the runways. D'Ariano et al. [13] deal with the development of a branch and bound algorithm for the ASP. D'Ariano et al. [14] include routing and scheduling decisions and solve the problem with a tabu search algorithm. Samà et al. [33, 34] develop a Mixed Integer Linear Programming (MILP) formulation to model the problem and develop a rolling horizon approach to solve the ASP without and with aircraft rerouting. However, the latter four works deal with the minimization of maximum delay. Samà et al. [35, 36] use the same MILP formulation of [33, 34] but with different objective functions, including the average delay and average travel time.

This paper builds on [32, 33, 34, 35, 36] with the substantial step forward of incorporating taxiway into the microscopic MILP model. The simultaneous scheduling of air and taxiway operations enables the evaluation of some taxi scheduling policies for take-off aircraft, such as "*wait-at-gate*" or "*free-the-gate*". With the former policy, when an aircraft leaves the gate it can reach the runway and depart without waiting on the taxiway. With the latter, an aircraft leaves the gate as soon as possible, possibly queueing on the taxiway before using the runway. The former policy is typically beneficial for the airlines and their passengers, since the passengers have more time to reach the gate, wait less on-board before take-off, and the company has reduced costs of fuel consumption. Moreover, it reduces the workload of ground controllers and allows larger buffer times for the other operations taking place at the gate, e.g., refuelling, cleaning, baggage handling, etc. The latter policy is potentially beneficial for the airport manager, since it allows using both the gates and the runways at full capacity, thus increasing the airport throughput. So far, costs and benefits of the two policies are difficult to evaluate, due to the lack of a Decision Support System (DSS) able to compute good schedules implementing the two policies.

Besides the two taxi scheduling policies, two air scheduling policies are analysed in this paper, related to the management of landing aircraft, named "*wait-on-route*" or "*free-the-route*". With the former policy, landing aircraft wait on the (airborne) route before the TCA or in pre-specified holding circles before the TCA, and enter the TCA only when they can land and reach the gate without further delay. With the latter policy, a landing aircraft enters the TCA as soon as possible, and it is managed by the controllers by using any time reserve, either on air or along the taxiway to the gate. The former policy typically simplifies the work of TCA controllers, since it avoids traffic congestion in the proximity of the runway, while the latter allows for a reduced workload of en-route controllers and reduced costs for the airlines due, e.g., to reduced landing delay and fuel consumption in case of large delays. On the other hand, the stress on the airport resources is larger.

The contribution of this paper is threefold. (i) The problem of coordinating aircraft scheduling operations on the taxiways and airways of an airport is formalized. Airport resources are divided into airspace and taxiway resources, with the runways at the border between the two domains. Microscopic optimization models, including relevant practical aspects such as inter-aircraft separation constraints and interdependent runways, are adopted to increase the level of realism of model and solutions. Four alternative objective functions are analyzed, based on aircraft delay and travel time, to take into account the preference of different stakeholders. (ii) Two taxi scheduling policies for take-off aircraft and two air scheduling policies for landing aircraft are formulated and analyzed; (iii) Solution methods are proposed and evaluated on practical-size instances from the Amsterdam Schiphol airport (AMS), the main international airport in the Netherlands, shown in Figure 1. Experimental results are very promising since optimal or near-optimal solutions are found within a short computation time.

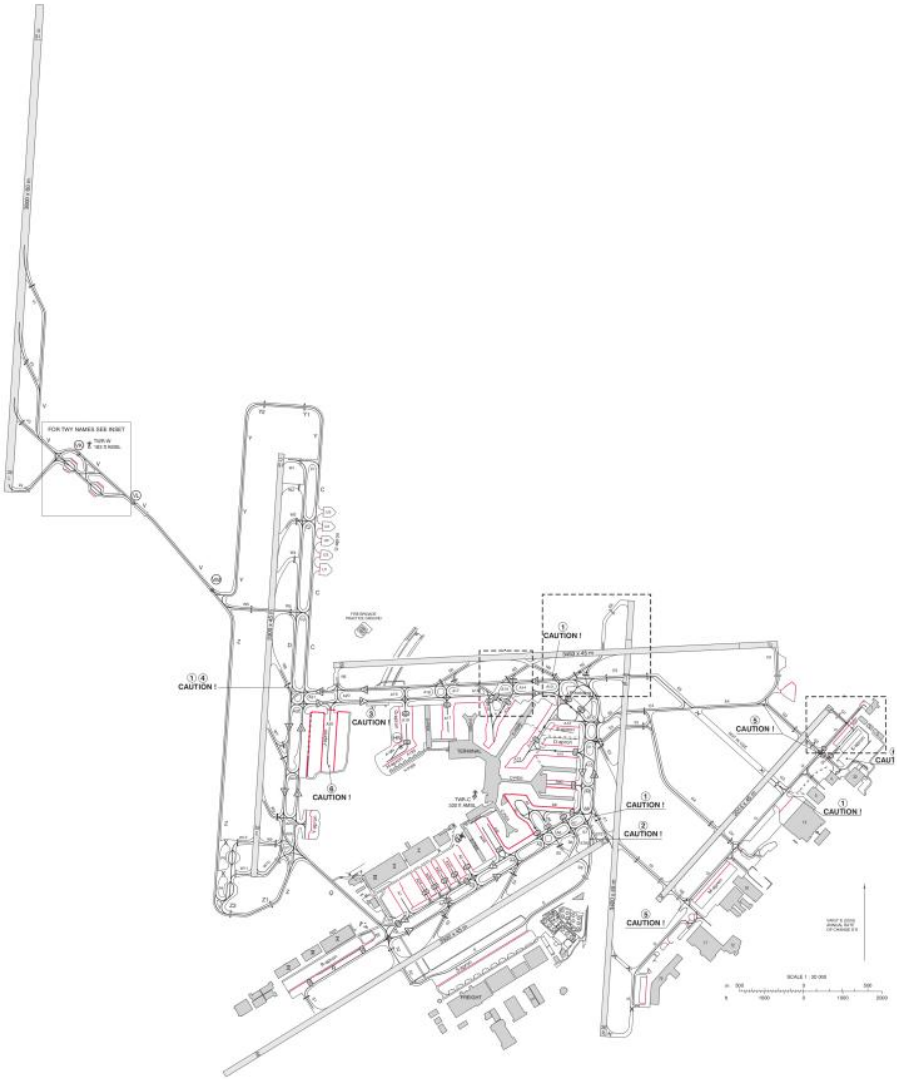

Figure 1: Layout of Amsterdam Schiphol Airport

The paper is organized as follows. Section 2 describes the ASP problem. Section 3 introduces the formulation of the mathematical formulations, including the modelling of problem constraints and objective functions. Section 4 describes the solution methods, which are then analysed in Section 5, reporting on the computational experience. Instances are based on the real operations at the Amsterdam Schiphol airport. Computational results are reported for different scheduling policies and performance indicators. Section 6 summaries the findings of this paper and draw directions for further research on the practical applicability of the proposed approaches.

2. Problem description

Large airports usually decompose the management of aircraft operations in several areas, each managed by an air traffic control authority. For example, Furini et al. [20] distinguish the Approach Radar Control (ARC), the Ground Control (GC) and the Tower Control (TC). The ARC manages the sequencing of landing aircraft from the border of the TCA to the runways, the GC manages the sequencing of taxiway operations from the gates to the runway holding points, before the runways. The TC is responsible for coordinating landing and take-off operations. We refer to ASP as the overall problem of coordinating taxiway, airway and runway scheduling decisions. We next describe

the main aspects that affect the feasibility of the ASP and its performance indicators.

Typically, each landing aircraft moves along a predefined route, i.e., a sequence of air segments, from its entry point in the TCA to the runway it is assigned to, following a standard descent profile. After the runway, it moves to the gate following the path prescribed by the GC. The ARC ensures that a minimum separation between every pair of consecutive aircraft in each air segment is maintained to avoid the effects of vortices generated by the feeder aircraft on the following aircraft, the exact value depending on the types, speeds and positions of the two aircraft. Similar separation constraints may also occur for pairs of aircraft moving on different routes. An example of this situation occurs on the so-called *common glide path*, i.e., the last air segment leading to different parallel runways before landing. In this case, besides the minimum longitudinal distance between consecutive aircraft landing on the same runway, a minimum diagonal distance between aircraft landing on different runways must be respected. Since each aircraft moves at standard speed in the TCA, the minimum separation distance can be converted into a minimum *separation time* between the entrance/exit of two aircraft in/from their respective air segments. Similarly, after the take-off aircraft move from the runway towards the assigned exit fix of the TCA along an ascent profile, again respecting the separation distances. Each runway can be occupied by at most one aircraft at a time, and a minimum separation time must be ensured from the leave of an aircraft to the entrance of the next one.

For each landing/take-off aircraft, a minimum and a maximum *traversing time* are given on the runway and on each air segment before/after the runway, computed according to its descendant/ascendant profile. In practice, the traversing time of each air segment may vary within limited margins, since the speed of each aircraft flying in the TCA can vary only in a small interval.

On the ground, each aircraft moves along a prescribed route between the assigned gate and runway, following a sequence of taxi segments. A ground segment has similarities and differences with an air segment, it is similar in that consecutive aircraft must keep a safety distance. It is different in that an aircraft can stop on the ground and wait until necessary, e.g., for the following resource to be freed. On the ground there are also *crossing points*, where two flows of aircraft moving in different directions intersect. A crossing point can be used by one aircraft at a time, it is therefore somewhat similar to a runway.

Real-time traffic control must ensure that all possible conflicts among aircraft at air and taxi segments, as well as at runways and crossing points are solved by adjusting the aircraft schedules. Specifically, a *potential conflict* occurs whenever two aircraft traverse the same resource, and there is a risk that they do not respect the minimum separation time required by traffic regulations. Note that separation times depend on the two aircraft involved in the potential conflict and on their respective routes. For this reason, the separation times are sequence-dependent. Clearly, the real-time position of each aircraft at the beginning of the planning horizon is also a constraint for the ASP, which can be modelled as a *release time*, i.e., the minimum time at which each aircraft can leave the gate or enter the TCA.

As far as the performance indicators of a schedule are concerned, Bennell et al. [9] list a number of indicators that are of interest for different stakeholders. Among those that are desirable from an Air Traffic Control (ATC) perspective they cite the maximization of the Runway Throughput (RT) and the minimization of: the Approach Time (AT) of aircraft, the Air Traffic Controllers' Workload (ATCW), the aircraft Taxi Time (TT), the arrival/departure delay. In this paper, all these indicators are taken into account. The free-the-gate policy aims at increasing RT as far as possible, ATCW is somewhat minimized under the wait-on-route policy, AT is reduced under the free-the-route policy, and TT is reduced under the wait-at-gate policy. The explicit minimization of AT or TT is addressed in the paper by using alternative objective functions, as well as the delay minimization, which is addressed by using two alternative objective functions: the minimization of the Maximum Delay (MD) or of the Average Delay (AD) with respect to a given *due date* computed for each aircraft.

An aircraft due date is computed as in [32, 33, 34, 35, 36]. Following a common ATC procedure, an on-time aircraft should take off within its assigned time window of 15 minutes, typically starting 5 minutes before the take-off published in the timetable and ending 10 minutes after the published take-off. The aircraft due date is therefore equal to 10 minutes after the published take-off time. An aircraft is late whenever it is not able to accomplish the departing procedure within its assigned time window. In this case, we assign a due date to late take-off aircraft equal to the minimum arrival time at the runway. Similarly, for on-time landing aircraft the due date is the published landing time, plus the minimum taxi time from the runway to the gate plus 10 minutes. For late landing aircraft the due date is the minimum arrival time at the gate.

3. Mathematical formulations of the ASP

This section presents the alternative graph formulation of the ASP constraints (Section 3.1). The MILP formulations based on the alternative graph representation of the problem and varying the objective function are then shown in Section 3.2. A numerical example of a fictitious airport with a few landing and take-off aircraft is provided in Section 3.3, in order to illustrate the alternative graph formulation and to discuss the optimal solutions obtained for the different scheduling policies.

3.1. Alternative graph model

The ASP problem can be formulated with an *alternative graph* [28], i.e., a triple $G = (N, F, A)$, where $N$is the set of nodes, F is a set of directed arcs and A is a set of pairs of directed arcs. Each arc in the sets F and A has associated a weight. Each node is associated to an event. With our notation, node Ai is associated to the entrance of aircraft A in resource i (air or ground segment, runway, crossing point), and t_{Ai} is the associated real variable denoting the entrance time of A in i. Two special nodes 0 and n are used to model the start of the schedule, i.e., time $t_0 = 0$, and its completion, i.e. t_n.

The arcs of the alternative graph model different types of constraints, with an approach similar to those used in space–time expansion networks, see, e.g., [38]. The weight of an arc (either fixed or alternative) always represents the minimum separation time between the two events associated to the nodes.

Arcs in the set F, *fixed*, model the aircraft routes and other fixed precedence constraints between pairs of events. Specifically, arc (Ai, Ah) of weight $w_{Ai,Ah}$ represents constraint $t_{Ah} \geq t_{Ai} + w_{Ai,Ah}$, as shown in Figure 2(a). Such arc is used, e.g., to model the entrance of aircraft A in two consecutive resources i and h along its route. In this case $w_{Ai,Ah}$ denotes the minimum traversing time of resource i. If i is an air segment, then aircraft A is also constrained by a maximum traversing time $w_{Ai,Ah} + \alpha_i$, where $\alpha_i \geq 0$ is the margin of flexibility allowed to aircraft A when traversing i. The resulting constraint $t_{Ah} \leq t_{Ai} + w_{Ai,Ah} + \alpha_i$ can be represented as in [12] by a backward arc (Ah, Ai) of weight $w_{Ah,Ai} = -w_{Ai,Ah} - \alpha_i$. Figure 2(b) shows the pair of fixed arcs modelling the traversing of an air segment. The case $\alpha_i = 0$ corresponds to a strict no-wait synchronization between events Ah and Ai.

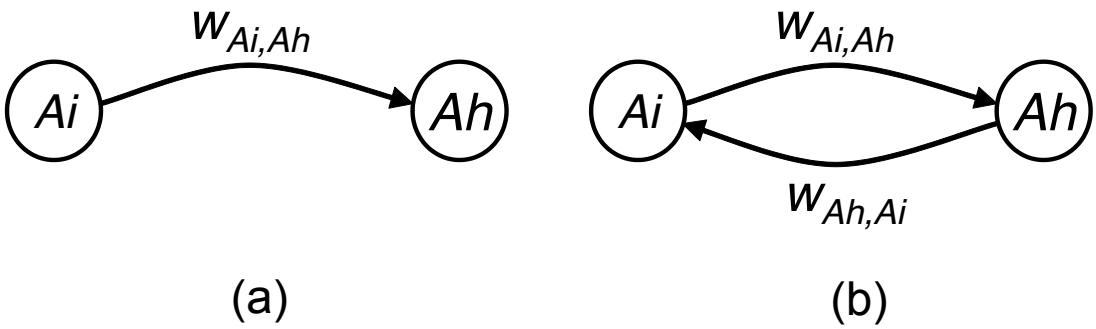

Figure 2: The fixed arcs for minimum traversing time (a) and minimum-maximum traversing time (b)

The model for the traversing of ground resources depends on the policy chosen for managing landing and take-off aircraft. Under the free-the-gate policy for take-off aircraft or the free-the-route policy for landing aircraft we use the model in Figure 2(a), since the aircraft can wait along its route and it is only constrained by the minimum traversing time. Under the wait-at-gate policy for take-off aircraft or the free-the-route policy for landing aircraft we use the model in Figure 2(b), with $w_{Ah,Ai} = -w_{Ai,Ah}$, since an aircraft cannot wait between the gate and the runway. We use the model of Figure 2(b) for the traversing of air segments under any policy, since aircraft cannot stop on air segments.

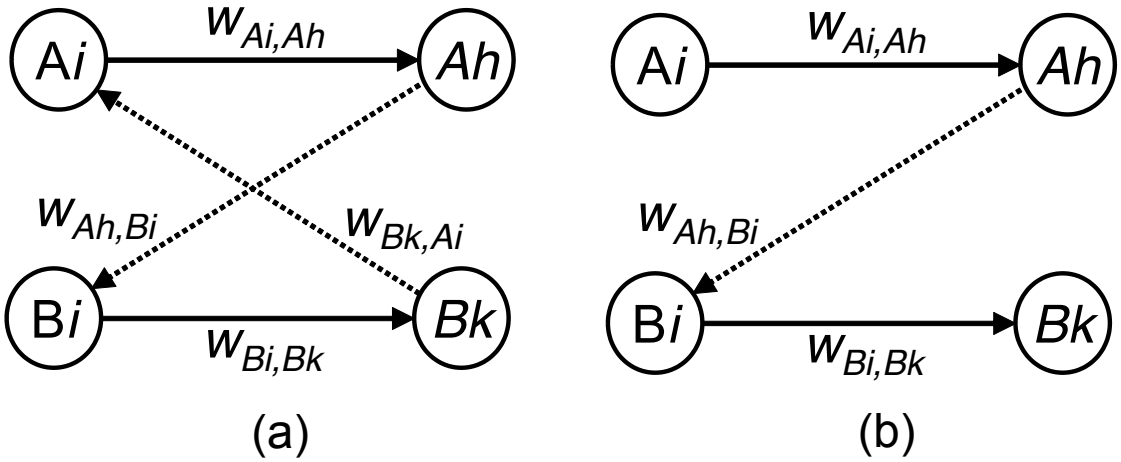

Figure 3: Two aircraft approaching the same runway or crossing point (a) and an ordering decision (b)

Arcs in the set A, *alternative*, model aircraft sequencing decisions. Given an alternative pair$[(Ah, Bi), (Bk, Ai)] \in A$, we say that arc (Ah, Bi) is the *alternative* of arc (Bk, Ai), and vice versa. In the ASP an alternative pair models the precedence between two aircraft on a conflicting resource. In a feasible solution to the ASP problem, exactly one of the two arcs from each pair must be chosen. A selection S is a set of alternative arcs, obtained by choosing one arc from each pair in the set A. A selection S is *feasible* if the connected graph $(N, F \cup S)$has no positive weight cycles, since a positive weight cycle represents an event strictly preceding itself, i.e., infeasible in practice. Given a feasible selection S, let $l^S(0, Ai)$ be a maximum weight path from node 0 to node Ai in graph $(N, F \cup S)$, the path weight being defined as the sum of the arc weights of the path. Then, a feasible schedule for all the aircraft is obtained by assigning entrance time $t_{Ai} = l^S(0, Ai)$to aircraft A on resource i, for all aircraft and resources. We next describe the alternative pairs for the different types of resources.

Figure 3(a) shows the alternative pair (dotted lines) when the conflicting resource i is a runway or a crossing point shared by two aircraft A and B. In the figure, we also represent the fixed arcs associated to the minimum traversing time of aircraft A and B on the resource i (solid arcs), omitting for simplicity the possible backward arcs. Figure 3(b) shows the solution in which aircraft A has precedence on B, i.e., (Ah, Bi) is chosen and B can enter resource i only $w_{Ah,Bi}$ after the exit of aircraft A (i.e., its entrance on the following resource h), the weight $w_{Ah,Bi}$ being the minimum separation time between the exit of aircraft A and the entrance of B. This corresponds to the constraint $t_{Bi} \geq t_{Ah} + w_{Ah,Bi}$.

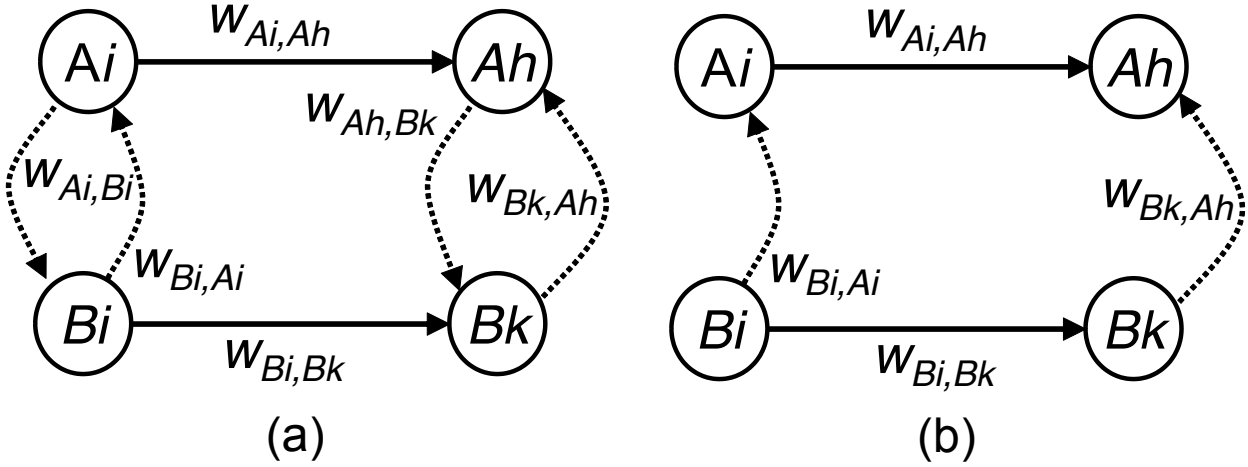

Figure 4: Two aircraft approaching the same air or taxi segment (a) and an ordering decision (b)

Figure 4(a) shows the sequencing decisions for two aircraft A and B on an air segment or a taxi segment i. As for the case of Figure 3(a), alternative arcs are depicted in dotted lines, fixed arcs are in solid lines and possible backward arcs are omitted. The entrance/exit of two consecutive aircraft in a segment is constrained by a minimum separation time. Moreover, overtaking is not allowed within the segment, i.e., the aircraft ordering must be the same at the entrance and at the exit in/form a segment. We ensure feasible sequencing through two pairs of alternative arcs, namely $[(Ai, Bi), (Bk, Ah)]$ and $[(Ah, Bk), (Bi, Ai)]$, where h and k (possibly equal) are the resources traversed by aircraft A and B after i, respectively. The weights on these arcs are equal to the (positive sequence-dependent) minimum separation time between aircraft A and B at the entrance/exit of segment i. Since a feasible selection cannot generate positive weight cycles in $(N, F \cup S)$, the choice of (Ai, Bi) from the first pair implies that of (Ah, Bk) from the second pair. Similarly, choosing (Bk, Ah) forces the choice of (Bi, Ai), as in Figure 4(b), thus ensuring the same ordering between aircraft A and B at the entrance from and exit to resource i.

Other fixed constraints are related to the special nodes 0 and n. A *release arc* (0, Ai) is used to model the entrance of an aircraft A in the first resource i of its route, see Figure 5(a), i.e., constraint $t_{Ai} \geq w_{0,Ai}$. The weight $w_{0,Ai}$ is the *release time* of aircraft A, defined in Section 2, i.e., the expected entrance time in the TCA for landing aircraft, or the expected departure time from the gate for take-off aircraft. A *due date arc* (Ai, n) is used to keep track of the delay of an aircraft A at the entrance of resource i on its route, see Figure 5(b), i.e., constraint $t_n \geq t_{Ai} + w_{Ai,n}$. The weight is negative and equal to $w_{Ai,n} = -d_{Ai}$, where d_{Ai} is the due date of aircraft A on resource i. We collect the delay of each aircraft at several points. For a take-off aircraft A we observe the time at which the aircraft leaves the runway and enters the exit air segment i. To compute the departure delay, the arc (Ai, n) is weighted with $w_{Ai,n} = -d_A$, where d_A is the due date of aircraft A, discussed in Section 2. For a landing aircraft A we set two due dates, one at the entrance of the TCA and one at the gate. The first one is equal to the release time $w_{0,Ai}$ of aircraft A, the second is the due date at the gate, defined in Section 2. We use the first value to record the extra time spent by the aircraft *en-route* before entering the TCA, while the second value allows the computation of the arrival delay at the gate. With this notation, the weight $l^S(0, n)$ of a maximum weight path from 0 to n in graph $(N, F \cup S)$, for a feasible selection S, is equal to the maximum delay associated to the schedule. Hence, minimizing the maximum delay corresponds to finding the feasible selection S^* minimizing the weight of a maximum weight path $l^{S^*}(0, n)$, as in [28].

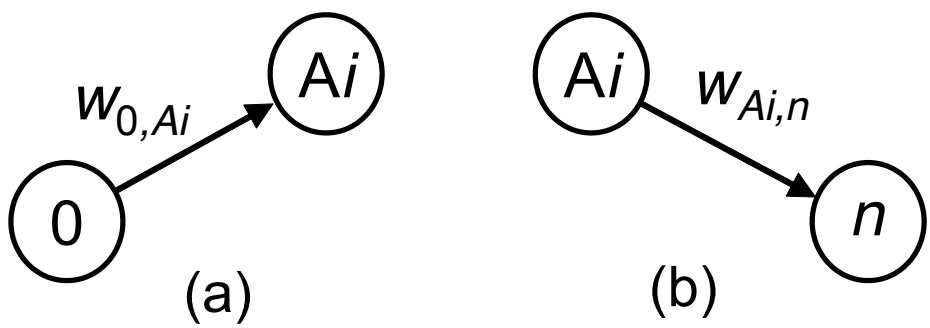

Figure 5: Aircraft release arc (a) and due date arc (b)

3.2. Mixed Integer Linear Programs

The alternative graph model can be translated into a MILP by keeping the $|N| - 1$real variables t_{Ai}, for all $Ai \in N$ plus t_n , and introducing $|A|$ binary variables, a variable $x_{AhBiBkAj} \in \{0,1\}$ for each pair $[(Ah, Bi), (Bk, Aj)] \in A$. The constraints are then the following (where M is a huge value):

$$t_{Bi} \geq t_{Ah} + w_{Ah,Bi} \quad \forall (Ah, Bi) \in F$$

$$t_{Bi} \geq t_{Ah} + w_{Ah,Bi} - M x_{AhBiBkAj} \quad \forall [(Ah, Bi), (Bk, Aj)] \in A$$

$$t_{Aj} \geq t_{Bk} + w_{Bk,Aj} - M(1 - x_{AhBiBkAj}) \quad \forall [(Ah, Bi), (Bk, Aj)] \in A$$

Setting $x_{AhBiBkAj} = 1$ makes constraint $t_{Bi} \geq t_{Ah} + w_{Ah,Bi} - Mx_{AhBiBkAj}$ always satisfied and constraint $t_{Aj} \geq t_{Bk} + w_{Bk,Aj} - M(1 - x_{AhBiBkAj})$ active, i.e., it corresponds to select arc (Bk, Aj) from pair $[(Ah, Bi), (Bk, Aj)]$ in the alternative graph. Setting $x_{AhBiBkAj} = 0$ corresponds to select arc (Ah, Bi) from pair $[(Ah, Bi), (Bk, Aj)]$.

The minimization of the Maximum Delay (min MD) in the MILP corresponds to the objective function min t_n. The MILP allows to easily formulating other objective functions keeping the constraints unchanged. Besides the maximum delay, we compute three objective functions:

- The minimization of the Average Delay (min AD) is:min $\sum_{(Ai,n)\in F} \max\{0, t_{Ai} - d_{Ai}\}$, where d_{Ai} is the due date of a node Ai(for which a due date has been set), and the sum is computed on all nodes with an associated due date.

- The minimization of the average Approach Time (min AT) is computed as follows. Let L be the set of landing aircraft, and let $Ae \in N$, $w_{0,Ae}$ and $Ar \in N$ be the node associated to the entrance of aircraft A in the TCA, its release time and the node associated to the arrival of aircraft A at the runway, respectively. Then, the approach time of aircraft A is $(t_{Ar} - w_{0,Ae})$ and the objective function min AT is min $\sum_{A\in L}(t_{Ar} - w0,Ae/|L|$.

- The minimization of the average Taxi Time (min TT) is computed as follows. Let $L$and T be the set of landing and take-off aircraft, respectively, and let $Ar \in N$, $Ag \in N$, $B\tilde{g} \in N$ and $B\tilde{r} \in N$ be the nodes associated to the arrival of $A \in L$ at the runway, the arrival of A at the gate, the departure of $B \in T$ from the gate and the departure of B from the runway. Then, the taxi time of aircraft A is $(t_{Ag} - t_{Ar})$, the taxi time of B is $(t_{B\tilde{r}} - t_{A\tilde{g}})$ and the objective function min TT is: min$\{\sum_{A\in L}(t_{Ag} - t_{Ar}) / |L| + \sum_{B\in T}(t_{B\tilde{r}} - t_{A\tilde{g}}) / |T|$.

3.3. Illustrative example

In this section, weshow a fictitious illustrative example with three aircraft, two landing (A, in red, and C, in green) and one take-off aircraft (B, in blue).

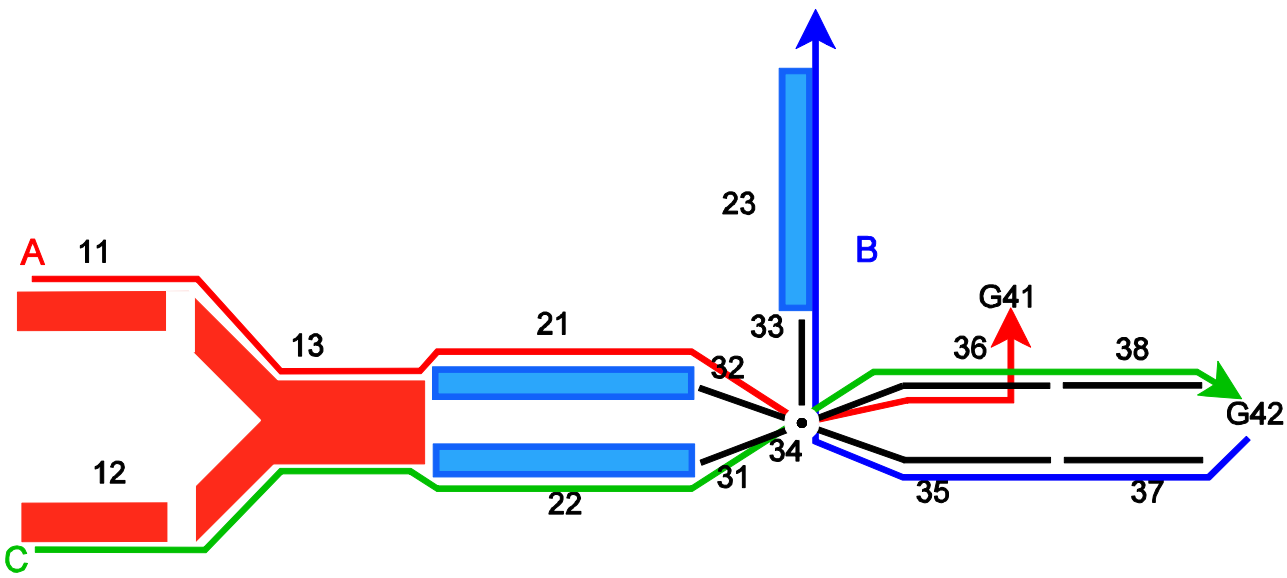

Figure 6: Layout of the toy example infrastructure

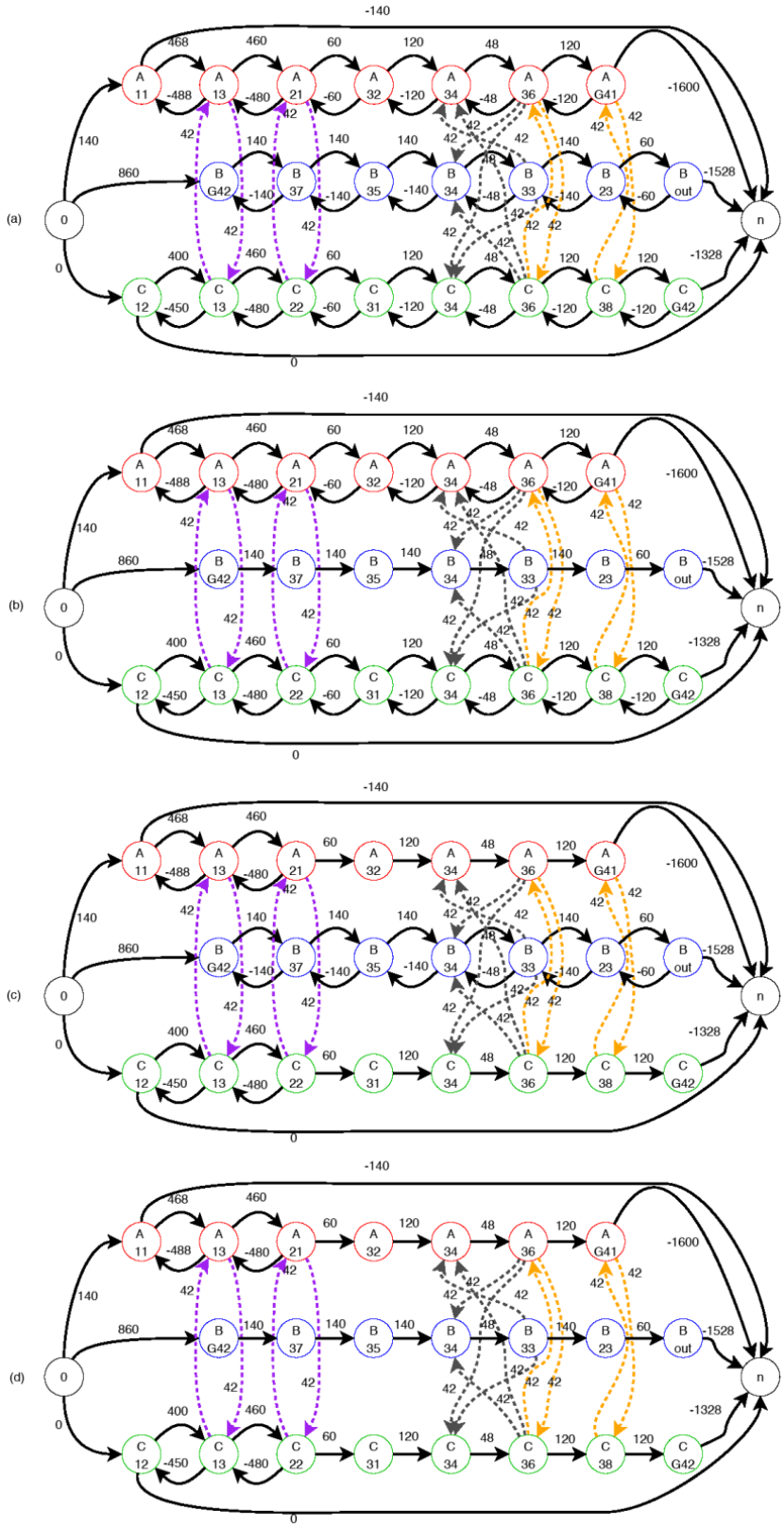

Figure 7: Alternative graphs for the illustrative example with the following policies:
(a) wait-at-gate wait-on-route; (b) free-the-gate wait-on-route; (c) wait-at-gate free-the-route; (d) free-the-gate free-the-route.

Figure 6 shows a schematic representation of the TCA. There are three airborne resources 11, 12 and 13 (depicted in red colour), the latter of which is a common glide path, i.e., two parallel air segments with a minimum diagonal separation, which are treated as a single resource with sequence dependent separation constraints. Ground resources consist of three runways 21, 22 and 23 (in blue), one crossing point 34 (depicted as black circles)and seven taxi segments 31, 32, 33, 35, 36, 37 and 38 (depicted in black), and two gates G41 and G42.

Aircraft A (in red) is a landing aircraft traversing two air segments (11 and 13), runway 21, two taxi segments (32 and 36), the crossing point 34, finally arriving at gate area G41. Aircraft C (in green) traverses in sequence resources 12, 13, 22, 31, 34, 36 and 38, finally arriving at gate area G42. Aircraft B (in blue) is a take-off aircraft starting from Gate area 42 and traversing resources 37, 35, 34, 33, 23, after which it takes off.

Figure 7 depicts the alternative graph formulation of this problem for the four combinations of policies formalized in Section 3.1. Figure 7(a) shows the combination wait-at-gate for take-off aircraft and wait-on-route for landing aircraft. Every row shows the fixed arcs (solid lines) associated to the route of one aircraft. Direct arcs (left to right) are weighted with the minimumtraversing time while backward arcs (right to left) are weighted with the maximum processing time (negative). For airborne segments there is a slack between minimum and maximum flow time, while on the ground a strict no-wait policy is imposed for each aircraft, as required by the selected policies. Dotted arcs represent alternative pairs.

For example, aircraft A and C share several resources, thus causing potential conflicts that require some alternative pairs to be modelled. The sharing of the common glide path 13 is modelled with two (violet) alternative pairs [(C13,A13),(A21,C22)] and [(C22,A21),(A13,C13)], for the crossing point 34 there is one (grey) pair [(A36,C34),(C36,A34)] and for the taxi segment 36 there are two (orange) pairs [(C36,A36),(G41,C38)] and [(C38,G41),(A36,C36)]. Aircraft B shares only the crossing point with the other two aircraft, which leads to other two alternative pairs (depicted with grey dotted colour in Figure 7).

For each aircraft there is a release date (140 for A, 860 for B and 0 for C) equal to the minimum entrance time in the area. For the take-off aircraft B there is a due date 1528, which is the latest take-off time after which the aircraft is late.

For the landing aircraft A and C there are two due dates each, one at the entrance in the area and one at the gate. The first due date equals the aircraft release time (but negative) and, if violated, measures the extra time spent en-route by the aircraft before accessing the TCA, the second due date indicates the latest arrival time at the gate area, after which the aircraft is late (1600 for A and 1328 for B).

The examples in Figure 7(b,c,d) depict the less constrained cases. In Figure 7(b) the take-off aircraft B follows the free-the-gate policy and therefore there are no backward arcs on ground resources for this aircraft. In Figure 7(c) the landing aircraft A and C follow the free-the-route policy and therefore there are no backward arcs on ground resources for these aircraft. Figure 7(d) depicts the less constrained case, since all aircraft follow the policy without backward arcs on ground resources.

Figure 8 shows the optimal solutions for the min MD objective associated to the alternative graphs of Figure 7. Specifically, Figure 8(a) shows the optimal solution for the alternative graph of Figure 7(a), i.e., for the combination wait-at-gate for take-off aircraft and wait-on-route for landing aircraft. Figure 8(b) shows the optimal solution for the alternative graph of Figure 7(d), i.e., for the combination free-the-gate for take-off aircraft and free-the-routefor landing aircraft. We do not report the optimal solutions for the other two cases since the optimal selection of alternative arcs for the case of Figure 7(b) is the same of that in Figure 8(a), while for the alternative graph in Figure 7(c) has the same selection of Figure 8(b). The maximum delay for the solution in Figure 8(a) is 58, obtained from the critical path 0,A11,A13,A21,A32,A34,A36,B34,B33,B23,Bout,n. The maximum delay for the solution in Figure 8(b) is 0, obtained from several critical paths, e.g., 0,C12,n.

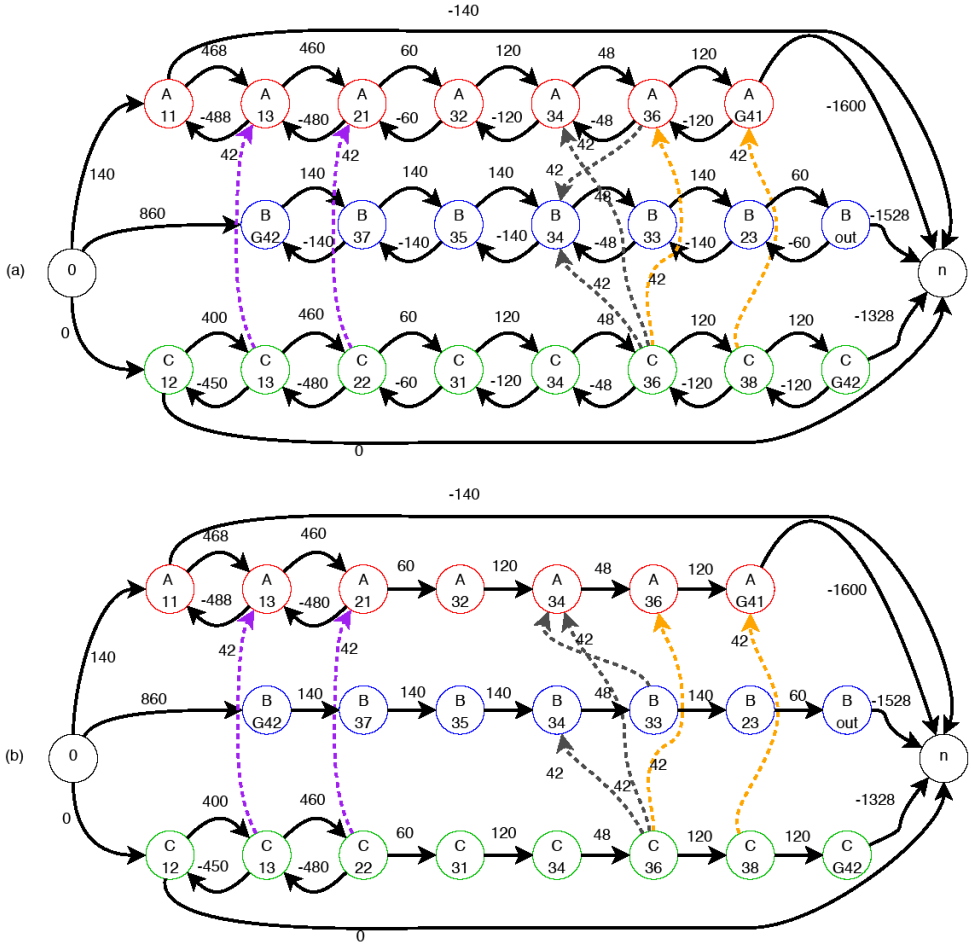

Figure 8: Optimal solutions for the illustrative example with policies: (a) wait-at-gate wait-on-route; (b) free-the-gate free-the-route

Table 1 shows four performance indicators for the four optimal solutions obtained by minimizing the min MD objective function for the alternative graph of Figure 7(a). In fact, there is the same optimal solution for the first two cases and for the latter two cases. Note that, even with this small example, different combinations of policy and objective may yield different results for the various indicators. For example, the minimization of TT under the Free-the-Gate/Free-the-Route policy combinationwould yield a different solution with TT = 1484 and MD = 58 (not shown in the table), i.e., the minimization of TT leads to increasing MD and vice versa. In the next section we study the trade-off among the different indicators on a realistic set of instances.

Table1: Test Results considering the four policies for the illustrative example

Policies	MD	AD	AT	TT
Wait-at-Gate Wait-on-Route	58	11.6	894	495
Free-the-Gate Wait-on-Route	58	11.6	894	495
Wait-at-Gate Free-the-Route	0	0	894	535
Free-the-GateFree-the-Route	0	0	894	535

4. Solution methods

Solution methods analyzed in this paper include the solution at optimality of the different MILP models with a commercial solver, namely the IBM-ILOG-CPLEX MILP solver. Optimal solutions are useful to assess the quality of both the heuristics methods and the policies addressed in this paper. The following fast heuristics (H1 and H2) have also been developed, based on the alternative graph model and implemented in the AGLibrary solver, a

software for scheduling problems developed at Roma Tre University, in Italy. Clearly, both heuristics can be used under different policies, achieving different ASP solutions.

4.1. Heuristic H1

The first heuristic is based on the observation that reducing the deviation from the First Come First Served (FCFS) sequence is commonly regarded as an element of fairness when solving the ASP [9]. For this reason, a heuristic procedure based on the FCFS sequence of landing/take-off operations is presented in the following, which at the same time is compliant with the four policies investigated in this paper. The FCFS sequence is first developed by considering the earliest landing/take-off time of each aircraft disregarding the conflict with other aircraft. This sequence corresponds to a partial selection S^p in the alternative graph. A feasible selection $S \supset S^p$ is then obtained by the Branch and Bound (BB) algorithm described in [14]. BB minimizes MD by exploiting a lower bound, based on the solution of a preemptive single-machine scheduling problem, as proposed in [15, 28]. It also makes extensive use of implication techniques, which allow the enlargement of a partial selection S^p whenever it can be proved that for some unselected pair of alternative arcs $[(Ah, Bi), (Bk, Aj)]$ the selection $S^p U(Ah, Bi)$ is infeasible. In this case (Bk, Aj)must be selected, i.e., S^p implies (Bk, Aj)**.** In this paper, we use the same lower bound and implications discussed in [14]. BB adopts a binary branching scheme, choosing an unselected alternative pair $[(Ah, Bi), (Bk, Aj)]$and generating two nodes: $S^p \cup \{(Ah, Bi)\}$ and $S^p \cup \{(Bk, Aj)\}$. Specifically, BB branches with priority on the alternative pairs associated to crossing points, since different traffic flows interact on these resources.

4.2. Heuristic H2

The second heuristic is based on the same idea of H1, but the feasible selection $S \supset S^p$ is obtained with fast greedy heuristics rather than with BB. The greedy heuristic starts with a partial selection S^p and, at each step, it adds to S^p an alternative arc from an unselected pair of the set A. The choice of the pair depends on the effect on the maximum weight path of the two arcs of the pair. Specifically, given an unselected alternative pair $[(Ah, Bi), (Bk, Aj)]$, let us consider the two selections: $S' = S^p \cup \{(Ah, Bi)\}$ and $S'' = S^p \cup \{(Bk, Aj)\}$, and the weight of the associated maximum weight paths $l^{S'}(0, n)$ and $l^{S''}(0, n)$. The AMCC rule [28] first chooses the unselected pair such that the quantity $\max\{l^{S'}(0, n); l^{S''}(0, n)\}$ is the largest among all the unselected pairs, and then add to S^p the alternative arc causing the smallest increase of the maximum weight path, i.e., the arc achieving the $\min\{l^{S'}(0, n); l^{S''}(0, n)\}$. The AMSP rule [28] first chooses the unselected pair such that the quantity $[l^{S'}(0, n) + l^{S''}(0, n)]$ is the largest among all the unselected pairs, and then add to S^p the alternative arc causing the smallest increase of the maximum weight path, i.e., the arc achieving the $\min\{l^{S'}(0, n); l^{S''}(0, n)\}$. H2 retains the best solution among those found by the two rules.

5. Experimental Results

We tested the traffic control system on a laboratory environment using real data of the Amsterdam Schiphol airport (AMS). The computational experiments are executed on a processor Intel Xeon (3.4 GHz), 32 GB Ram and Windows operating system. The next two subsections provide a description of the case study and ASP instances addressed in this paper. Then, a detailed quantitative comparison is reported on the performance of various MILP formulations solved with the IBM-ILOG-CPLEX MILP solver, when varying the scheduling policy and the performance indicator to be optimized. We also present the performance of the two heuristics H1 and H2 described in Section 4.

5.1. Case study

The instances considered in this paper are derived from real scheduling data collected for the Amsterdam Schiphol airport, shown in Figure 1. In our case study, only four of the six runways are used, as it is in the typical operating mode of this airport. Also not all ground resources are used for taxiways in the considered instances. Figure 5 shows a schematic representation of the airborne and ground resources actually used in our case study. There are 7 gates areas (A…G), 16 air segments for landing operations (depicted in red colour), 2 air segments for take-off operations (depicted in green), 4 runways (depicted in blue), 14 ground segments (depicted in black) and 2 crossing points (depicted as black circles). Two runways are dedicated to landing operations (connected to red air segments) while the other two are dedicated to take-off operations (connected to green air segments).

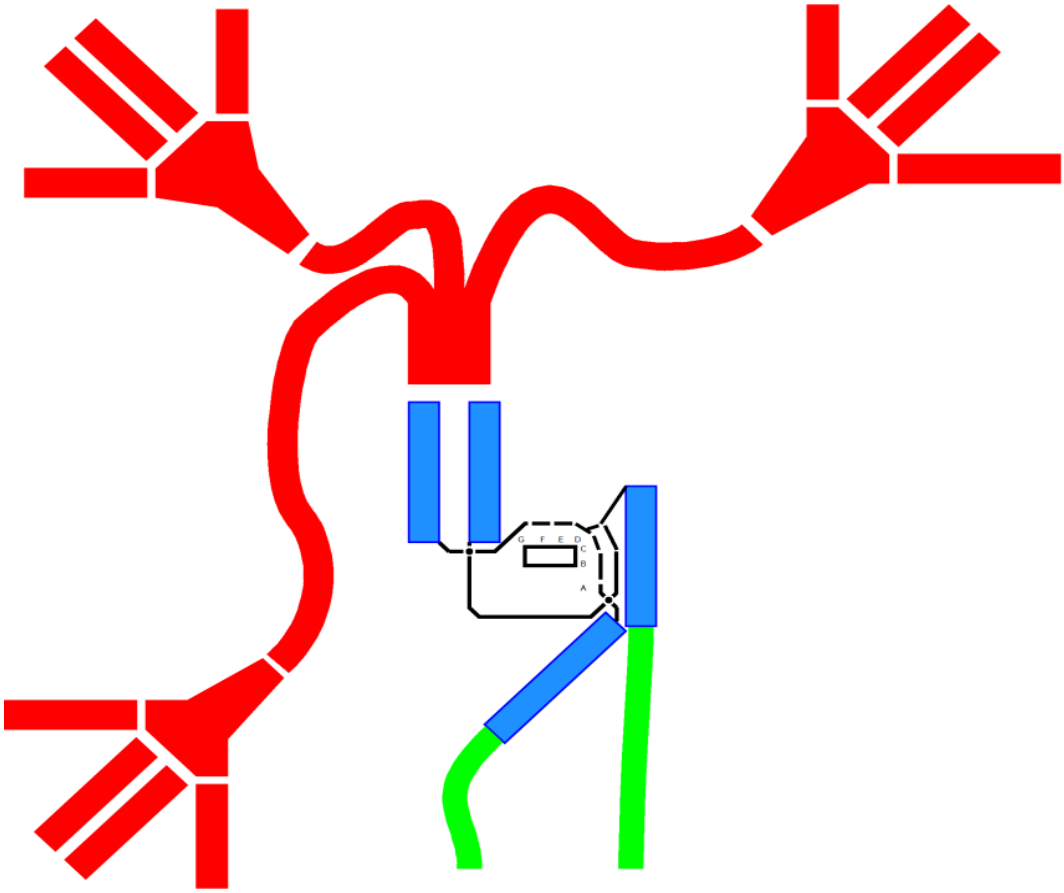

Figure 9: A schematic layout of the Amsterdam Schiphol airport area

5.2. ASP instances

The instances are built by considering one hour of operations on atypical day of traffic, corresponding to a timetable with 70 aircraftpartitioned into four different size categories (heavy, medium, small and light), with different characteristics of minimum separation time.The assignment of each aircraft toa gate area and a runway is given (randomly generated, such that the instance with all on-time aircraft is conflict-free), as well as the route on ground and airborne resources (equal to a shortest path).

From the timetable, we generated 30 ASP instances for each scheduling policy (and four policies, for a total of 120 ASP instances). Each instance is generated by assigning to each aircraft an initial delay, computed as follows. From the observation of the realized delays over five days, the best-fitting 3-parameter Weibull probability distribution has been generated, respectively for short haul arrivals, long haul arrivals, and departures, shown in Figure 6 (a, b and c, respectively). In Figure 6, the horizontal axis reports the observed aircraft arrival/departure deviation with respect to the scheduled time in seconds (negative deviation means earliness, positive means tardiness), the vertical axis reports the probability of a given deviation. The histograms report the observed values and the solid lines the approximating Weibull probability density function. On average, arrivals are early by 922 sec and departures are late by 356 sec. Specifically, for the arrivals the average positive deviation [negative deviation] is 653 sec [-1315 sec], while for the departures the average positive deviation [negative deviation] is 549 sec [-216 sec].

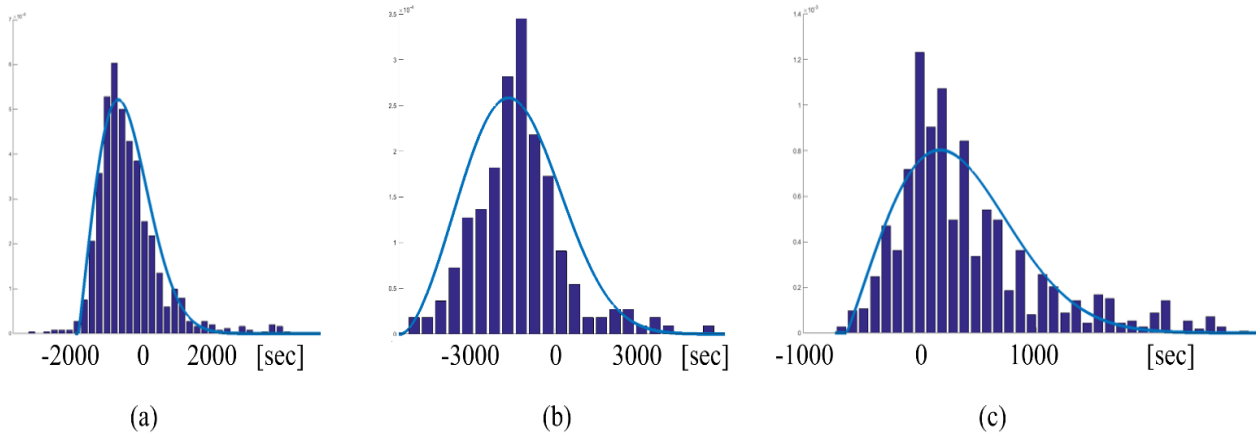

Figure 10: Probability density functions of short haul arrivals (a), long haul arrivals (b), and departures (c)

Table 2 reports average information on the size of the ASP instances tested in this paper, namely the number of landing and take-off aircraft simulated in each instance, and on the size of the alternative graph: number of nodes in *N*, fixed arcs in *F*, and alternative pairs in the set *A*. Specifically, sets *N* and *A* have the same size over all instances, while the size of set *F* depends on the chosen policy. Table 2 reports the minimum and maximum values of set *F*.

Table 2: Average information of the ASP instances

Landing Aircraft	Take-off Aircraft	|*N*|	Min |*F*|	Max |*F*|	|*A*|
35	35	652	1001	1266	9448

5.3. Computational results

Table 3 presents the optimal solutions for each MILP formulation solved by the IBM ILOG CPLEX MILP 12.0 solver. We consider 16 MILP formulations, obtained by combining a scheduling policy for landing/take-off with an objective function. Each row of the table gives average results on the 30 ASP instances described in Section 5.2. Besides the optimal value of the objective function (indicated by an asterisk), for each solution we compute all the four performance indicators of Section 3.2 in Column 2-5. Column 6 reports the average computation time required by the MILP solver. All results are reported in seconds.

Table 4 is similar to Table 3 but, in this case, Pareto-optimal solutions are shown. In fact, Table 3 reports the results achieved when minimizing only one objective at a time. Therefore, it might be the case that there are other solutions with the same optimum for the objective function and better values for the other indicators. To better investigate this fact, a new set of experiments has been performed as follows. In order to obtain a Pareto-optimal solution, each instance is modified by adding a constraint in which the objective function is constrained to be equal to the optimum and the objective function is now a linear combination of the other three indicators, the weight being equal to the minimum for each individual indicator. Column 6 reports the average cumulative time that is required by the MILP solver for the solution of this new set of instances at proven optimality, including the first step of optimization reported in Table 3

Table 3: Results on the 16 MILP formulations

MILP Formulation	MD (sec)	AD (sec)	AT (sec)	TT (sec)	Comp. Time (sec)
Min MD					
Wait-at-Gate Wait-on-Route	233*	18	1247	1069	15
Wait-at-Gate Free-the-Route	200*	15	1236	1107	17
Free-the-Gate Wait-on-Route	184*	14	1226	1098	13

Free-the-GateFree-the-Route	170*	13	1218	1102	14
Min AD					
Wait-at-Gate Wait-on-Route	316	11*	1230	1069	37
Wait-at-Gate Free-the-Route	283	9*	1224	1104	62
Free-the-Gate Wait-on-Route	244	9*	1215	1094	24
Free-the-GateFree-the-Route	221	8*	1212	1101	35
Min AT					
Wait-at-Gate Wait-on-Route	4447	111	1172*	1069	21
Wait-at-Gate Free-the-Route	3327	72	1172*	1123	32
Free-the-Gate Wait-on-Route	559	22	1172*	1114	21
Free-the-GateFree-the-Route	500	20	1172*	1114	29
Min TT					
Wait-at-Gate Wait-on-Route	1209	71	1347	1069*	8
Wait-at-Gate Free-the-Route	1112	61	1315	1069*	8
Free-the-Gate Wait-on-Route	1039	46	1279	1069*	8
Free-the-GateFree-the-Route	1028	46	1287	1069*	8

Table 4: Results for Pareto-optimal solutions on the 16 MILP formulations

MILP Formulation	**MD (sec)**	**AD (sec)**	**AT (sec)**	**TT (sec)**	**Comp. Time (sec)**
Min MD					
Wait-at-Gate Wait-on-Route	233*	13	1241	1069	40
Wait-at-Gate Free-the-Route	200*	11	1229	1104	70
Free-the-Gate Wait-on-Route	184*	10	1221	1094	27
Free-the-GateFree-the-Route	170*	9	1215	1100	43
Min AD					
Wait-at-Gate Wait-on-Route	316	11*	1228	1069	258
Wait-at-Gate Free-the-Route	279	9*	1220	1103	277
Free-the-Gate Wait-on-Route	244	9*	1211	1093	255
Free-the-GateFree-the-Route	219	8*	1209	1100	158
Min AT					
Wait-at-Gate Wait-on-Route	2432	64	1172*	1069	69
Wait-at-Gate Free-the-Route	1289	36	1172*	1151	147
Free-the-Gate Wait-on-Route	410	16	1172*	1105	63
Free-the-GateFree-the-Route	364	14	1172*	1106	77
Min TT					
Wait-at-Gate Wait-on-Route	274	13	1229	1069*	89
Wait-at-Gate Free-the-Route	274	12	1218	1069*	159
Free-the-Gate Wait-on-Route	270	12	1224	1069*	68
Free-the-GateFree-the-Route	267	12	1216	1069*	133

The results shown in Tables 3 and 4 allow evaluating the different policies and objectives from several perspectives:

- The more constrained policies (wait-at-gate and wait-on-route) tend to increase delays (MD and AD), as expected, the penalisation being severe when min AT is the MILP objective function. In fact, in the latter case, min AT disregards take-off aircraft and gives priority to landing aircraft, thus causing strong delays for take-off aircraft. In general, min MD and min AD are more sensitive to the policy being used

with respect to min AT and min TT, since for the latter functions the optimum is independent from the adopted policy.

- The stand-alone minimization of travel-time related objectives (min AT and min TT), from Table 3, tends to penalise delays indicators (MD and AD) severely. For min TT, after the second step of optimization shown in Table 4, the other indicators decrease to near-optimum. This fact means that there are many solutions optimal for min TT and ranging from very good to very bad for AD and MD. For min AT, the second step of optimization reduces MD and AD but the solutions are still bad for these indicators, i.e., there are no solutions optimal for min AT and good for MD and AD. The vice versa is not true, i.e., min MD or min AD does not deteriorate much AT and TT indicators. This result suggests that the minimization of delay-related objective functions should be preferred to other performance indicators, and somewhat seems to justify the common preference of researchers and practitioners for these objective functions.

- Comparing the performance of min MD and min AD on the four criteria, min MD tends to distribute delays among aircraft more uniformly than min AD. In fact, the difference between the maximum and average delays is significantly smaller with min MD, compared to min AD.

- When the computation times are considered, it can be observed that the MILP solver is faster with min MD than with min AD, the latter objective requiring the largest computation time among the four indicators.

Table 5 shows the results obtained by the heuristic H1 of Section 4 for the same indicators of Table 3. Each row reports the average performance of the same 30 instances of Table 3. As shown in the last column, H1 is faster than the commercial solver. Comparing its performance with min MD and min AD, from Table 3, it can be observed that the heuristic achieves intermediate results in terms of maximum and average delay, though its performance is worse in terms of AT and TT indicators. The relatively good results of this heuristic seem to justify the common preference practice of air traffic controllers of adopting a FCFS-based sequence on the runways, even if the overall model is required to compute a globally feasible solution.

Table 5: Performance of the heuristic H1 for different policies

Policy	MD(sec)	AD (sec)	AT (sec)	TT (sec)	Comp. Time (sec)
Wait-at-Gate Wait-on-Route	250	17	1262	1069	5
Wait-at-Gate Free-the-Route	220	14	1245	1146	9
Free-the-Gate Wait-on-Route	188	12	1237	1097	4
Free-the-GateFree-the-Route	176	10	1230	1141	8

Table 6 shows the results obtained by H2. Also in this case, each row reports the average performance of the same 30 instances of Table 3. H2 is the fastest method as its computation time is always within one second of computation. Clearly, the short computation time has a price in terms of (MD, AD, AT) performance deterioration with respect to H1, though TT slightly improves with respect to H1.

Table 6: Performance of the heuristic H2 for different policies

Policy	MD (sec)	AD (sec)	AT (sec)	TT (sec)	Comp. Time (sec)
Wait-at-Gate Wait-on-Route	271	18	1267	1069	1
Wait-at-Gate Free-the-Route	238	15	1247	1129	1
Free-the-Gate Wait-on-Route	192	12	1238	1094	1
Free-the-GateFree-the-Route	183	11	1230	1138	1

6. Conclusions

This paper investigates the ASP, i.e., the problem of coordinating aircraft scheduling operations on the taxiways and airways of an airport. ASP is formulated with microscopic optimization models including relevant practical aspects arising both in the airways and on the ground. Four scheduling policies are incorporated into the model and evaluated in combination with four relevant performance indicators, taking into account aircraft delay and travel time. Solution methods are proposed and evaluated on practical-size Amsterdam Schiphol airport instances, yielding very promising results in terms of both solution quality and computation time. The knowledge of the optimal solutions for all the tested instances allows the overall assessment of the different policies and indicators, demonstrating that delay-based objective functions are likely preferable with respect to travel time-based objectives. Moreover, the analysis confirms that the common approach of scheduling aircraft focusing on the runways and on the FCFS approach are quite effective, yielding good results within a short computation time. However, the use of the overall model is necessary to ensure the globally feasibility and quality of the ASP solution compared to all the airport operations.

Regarding the various scheduling policies, the most constrained policy (i.e. wait-at-gate wait-on-route) forces the TT to be minimum in all ASP solutions at the cost of deteriorating the value of the objective function and the other indicators. The less constrained policy (i.e. free-the-gate free-the-route) with objective function min MD, min AD or min AT exhibits better performance in terms of the three indicators MD, AD and AT compared to the more constrained policies. However, since it does not take into account TT directly, the latter indicator deteriorates. The other two policies find intermediate quality solutions, and act as a compromise among different performance indicators.

Further research should be dedicated to the closed-loop control, i.e., to aircraft rescheduling in response to disturbances arising on-line, as well as to the integration of rescheduling algorithms within real-time traffic control systems. Another important line of research should address the implementation of more efficient and effective algorithms for collaborative decision making at airport resources and between different airports to handle multi-airport traffic disturbances.

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