EFFECTIVENESS OF OPTIMAL AIRCRAFT REROUTING STRATEGIES FOR THE MANAGEMENT OF DISTURBED TRAFFIC CONDITIONS

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ABSTRACT

This paper addresses the real-time aircraft conflict detection and resolution problem in a Terminal Manoeuvring Area (TMA). This problem is to take real-time airborne decisions on take-off and landing operations at a congested airport in given time horizons of traffic prediction. The possible aircraft control actions at each air segment and runway in the TMA are speed adjustment, sequencing, holding and routing. We consider rescheduling and rerouting decisions in the TMA to dynamically search for alternative air segments and to balance the load of each runway. The objective function is the minimization of delay propagation and the decision variables are the aircraft timing and routing decisions. This problem can be viewed as a job shop scheduling problem with additional real-world constraints. We study this problem by using alternative graphs. We investigate the effectiveness of aircraft rerouting strategies, incorporated in a state-of-the-art tabu search scheme. The effectiveness of solution algorithms are evaluated on practical size instances from the Milano Malpensa airport, in Italy. Disturbances regarding the entrance time of aircraft in the TMA are simulated for assessing the optimization models and procedures under congested traffic conditions. Entrance delays simulate perturbed traffic conditions, due e.g. to adverse weather conditions. The computational results also demonstrate the effectiveness of the tabu search algorithm to reduce delays and travel times when compared with the heuristic and exact aircraft scheduling solutions.

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INTRODUCTION

This paper deals with the development of advanced optimization approaches for improving the real-time management of disturbed aircraft operations at busy airports. From a logical point of view, Air Traffic Control (ATC) decisions in a TMA can be broadly divided into: (i) Routing decisions, where an origin-destination route for each aircraft has to be chosen regarding air segments and runways; (ii) Timing decisions, where routes are fixed under traffic regulation constraints and aircraft passing timing have to be determined in each air segment, runway and (eventually) holding circle. In practice, routing (i) and scheduling (ii) decisions in a TMA are taken simultaneously and a given performance index is optimized. The main objective of routing decisions is typically to balance the use of critical resources (e.g., alternative runways, air corridors) while the whole process is to limit aircraft delays [1].

Decision Support Systems (DSSs) based on optimization algorithms may help to exploit at most the capacity available in a TMA during operations. In this context, the optimization of take-off/landing operations is an important factor to improve the performance of the entire ATC system. However, ATC operations are still mainly performed by human controllers with only a limited aid from automated systems. In most cases, computer support consists of a graphical representation of the current aircraft position and speed. As a result, the delay propagation is not effectively limited during landing and take-off operations.

For each TMA, landing aircraft move along predefined routes from an entry fix to runway following a standard descent profile. During all the approach phases, a minimum separation between every pair of consecutive aircraft must be guaranteed. This standard separation depends on the type and relative positions of the two aircraft (at the same or different altitude). By considering the different aircraft speeds, the safety distance can be translated in a separation time. Similarly, departing aircraft leave the runway moving towards the assigned exit fix along an ascent profile, respecting separation standards. The runway can be occupied by only one aircraft at a time, and a separation time should be ensured between any pair of aircraft. Once a landing/departing aircraft enters the TMA it should proceed to the runway. However, airborne (ground) holding circles can be used to make aircraft wait in flight (at ground level) until they can be guided into the landing (take-off) sequence. Real-time traffic management copes with potential aircraft conflicts by adjusting the off-line plan (timetable) in terms of retiming, reordering, rerouting and holding actions. A conflict occurs whenever aircraft traversing the same resource (i.e. air segment or runway) do not respect the minimum separation time required for safety reasons. Separation times depend not only on the aircraft sequence but also on the route chosen for consecutive aircraft.

The Aircraft Conflicts Detection and Resolution (ACDR) problem has been the subject of several studies (see the literature reviews in [2-5]). The ACDR models can be broadly classified as basic or detailed. In the basic models only the runways are included in the TMA, while detailed approaches also model the air segments. In general, basic models are more tractable than detailed models and may lead to useful insights for the problem. At the same time, they are less realistic since bottleneck situations may also happen in air segments of the TMA and in any case a solution that is feasible for a basic model may not be feasible in practice. The basic model has been investigated in [6-14], while detailed approaches are studied in [15-16]. However these works are concentrated on the scheduling problem only. Our goal is to extend the problem to the possibility of routing flexibility with the detailed approach.

Recent studies have been dedicated to a complementary problem that is the ATFM (Air Traffic Flow Management) problem in large networks with multiple airports [17-19]. Their approach presents a broader view on delay propagation compared to TMA models but the adopted models are macroscopic and potential conflicts between aircraft are not visible at the level of air segments and runways but in terms of aggregated flight paths only.

This paper focuses on the real-time control problem to provide optimal conflict-free airborne decisions at the TMA. Similar problems are also studied in railway transportation field for reordering and rerouting problems [20-21]. However, the two types of problems have a quite different structure and require careful adaptation of existing models and algorithms.

In a recent work on the ACDR problem with fixed routes, that is an NP-complete problem, we developed a branch and bound algorithm in which aircraft routes are decided at preliminary step [22]. In this work the ACDR problem with flexible routing is addressed. Due to the problem complexity, we divide it into two subproblems. A rerouting problem, in which a route among a set of rerouting possibilities is associated to each aircraft, and a scheduling problem in which a start time is assigned to each operation.

The ACDR problem is modelled as a generalized job shop scheduling problem and is formulated via alternative graphs [23], that are able to enrich the model of [16] by including additional real-world constraints, such as holding circles, time windows for aircraft travel times, multiple capacity of air segments and blocking constraints at runways. This formulation allows accurate modelling of future air traffic flows on the basis of the actual aircraft positions and speeds, and safety constraints. We investigate the performance of reordering and rerouting algorithms for ACDR on practical size instances of the Milano Malpensa (MXP) airport. The structure of the airport is introduced in the following sections together with an example of the alternative graph formulation.

The problem of reacting to disturbed traffic conditions is a key issue in air traffic control practice (see, e.g., [24, 25]). In [26], we proposed preliminary experiments on a runway rerouting strategy have been proposed for Rome Fiumicino airport. In this paper, we consider two rerouting strategies are considered: air and runway rerouting. The larger flexibility is due to an increased number of aircraft routes in air segments. We consider randomly delay scenarios in order to simulate disturbed traffic conditions. The optimization procedures are evaluated in terms of delay minimization and travel time spent by each aircraft.

DECISION SUPPORT SYSTEM

Figure 1 describes the architecture of our system for decision support, structured similarly to the one proposed in [21] for railway traffic control. The decision support system is in charge of computing a feasible aircraft schedule and then looking for better aircraft routing solutions.

Given a timetable, the current status of the network, a default defined route and a set of rerouting options for each aircraft, the aircraft rescheduling module returns a feasible schedule for the given aircraft routes. At the first run the scheduling module considers the default routes. If no feasible schedule is found within a predefined time limit of computation, human dispatcher is in charge of recovering infeasibilities by taking some stronger decisions (forbidden to the automated system), such as rerouting some aircraft to a different airport. When a feasible schedule is found, the aircraft rerouting module verifies whether a rerouting option, leading to a potentially better solution, exists. In general, our procedure is designed to work with multiple rerouting options. However, in our computational experiments the rerouting module changes one aircraft route at each iteration. For each changed route, aircraft running times and separation times in our problem formulation are modified accordingly, as describe in the next section. Whenever rerouting is performed, the aircraft rescheduling module computes a new conflict-free timetable by thoroughly rescheduling aircraft movements. The iterative rescheduling and rerouting procedure returns the best solution found when a given computation time is reached or no rerouting improvement is possible.

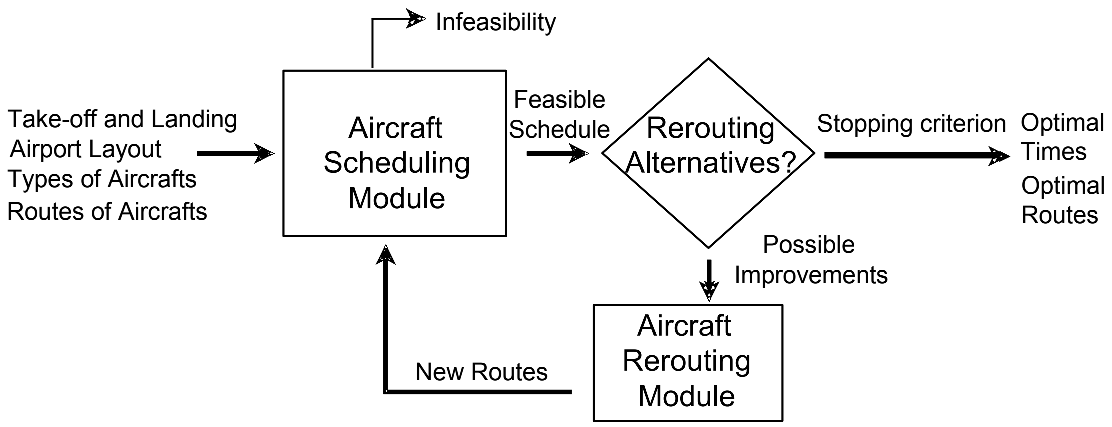

Figure 1: Schematic view of the decision support system

The aircraft scheduling subproblem is solved by using the branch and bound (BB) procedure of [22]. The search scheme used in this paper branches with priority on sequencing aircraft on the runways.

The aircraft rerouting subproblem is solved by a tabu search (TS) based on the approach of [20]. A detailed description of the algorithmic setting of TS can be found in [27].

PROBLEM DESCRIPTION AND FORMULATION

This section introduces the ACDR problem, describes our model and gives illustrative examples.

The ACDR problem consists of choosing a route for each aircraft and conflict-free timings for all chosen routes such that separation times between aircraft are satisfied, no aircraft enters the network before its release time and consecutive delays are minimized. The main goal of this rescheduling process is to reduce aircraft delays in the TMA, while satisfying traffic regulation constraints and the compatibility with the real-time position of each aircraft. The latter information enables the computation of its release time, which is the minimum time at which the aircraft can enter the network.

Aircraft delays are computed as follows. A departing aircraft is supposed to take-o within its assigned time window and is late whenever it is not able to accomplish the departing procedure within its assigned time window. In our model, we follow the procedure commonly adopted by air traffic controllers that consider a time window for take-off between 5 minutes before and 10 minutes after the Scheduled Take-off Time (STT). A departing aircraft is late if leaving the airport after 10 minutes from its STT. Arriving aircraft are late if landing after their Scheduled Landing Time (SLT). The aircraft delay is partly due to the entrance delay in the TMA and partly due to the additional delay caused by the resolution of potential aircraft conflicts. We minimize this second part, that is called consecutive delay [20-22]. Precisely, we minimize the maximum consecutive delay that is the largest deviation due to the resolution of potential conflicts in the TMA during the time horizon of traffic prediction under study. With this approach, all aircraft have the same relevance to the objective function while the minimization of the total aircraft delay would focus on the aircraft with the largest entrance delay (specially if this value is much greater than the entrance delay of the other aircraft) or on the last aircraft travelling in the TMA during the studied time horizon (possibly with no conflict with the other aircraft and therefore with no need of rescheduling).

We now introduce further notation before giving the alternative graph formulation of the ACDR problem. The traversing of an air segment or runway by an aircraft is known as operation. Each aircraft has associated a route that is denoted as the sequence of operations related to this aircraft, i.e., the sequence of operations to be executed on air segments, holdings or runways. The variables of the ACDR problem are the set of operations to be performed by each aircraft (routing decisions) and the start time t_i of each operation i (timing decisions). A timing specifies the start time of each operation in the route.

Given an operation i, we denote with $\sigma(i)$ the operation which follows i on its route and with f_i a minimum processing time of operation i. A timing is feasible if $t_{\sigma(i)} \geq t_i+f_i$, for every operation in the route (as for the examples of Figures 2 and 3). A set of feasible route timings is conflict-free if, for each pair of operations associated to the same resource, the minimum separation constraints are satisfied.

The ACDR problem can be represented by an alternative graph that is a triple $G = (N, F, A)$, where $N = \{0, 1, \ldots, n, *\}$ is the set of nodes, F is a set of directed arcs and A is a set of pairs of directed arcs. Each node $1 \ldots n$ is associated to the start time t_i of operation i, i.e., to the entrance of the associated aircraft in the associated resource. Additional nodes 0 and * are used to model the start and completion of the schedule. Arcs in the set F, conjunctive, model aircraft routing decisions. Each fixed arc of the set F is associated to the processing of an operation i and has weight f_i. Arcs in the set A, alternative, model aircraft sequencing and holding decisions. If $((i, j), (h, k)) \in A$, arc (i, j) is the alternative of arc (h, k). Each alternative arc (i, j) has an associated weight f_{ij}. A selection $S(F)$ is a set of alternative arcs, at most one from each pair. A selection, in which exactly one arc is chosen from each pair in A, is a feasible schedule (i.e., a solution to the ACDR problem) if the connected graph $(N, F, S(F))$ has no positive length cycles. Given a feasible schedule $S(F)$, a timing t_i for operation i is the length of a longest path from 0 to i (i.e., $l^{S(F)}(0, i)$). A feasible schedule $S(F)$ is optimal if $l^{S(F)}(0, *)$ is minimum over all the solutions.

In Figure 2 (a-b), i and j are the operations associated the entrance of two aircraft in a runway (blocking resource). When i precedes j (Figure 2 b) the separation constraint requires that aircraft associated to j must respect the minimum separation constraint: $t_j \geq t_{\sigma(i)} + f_{ij}$. Similarly, if j precedes i, $t_i \geq t_{\sigma(j)} + f_{ji}$ holds.

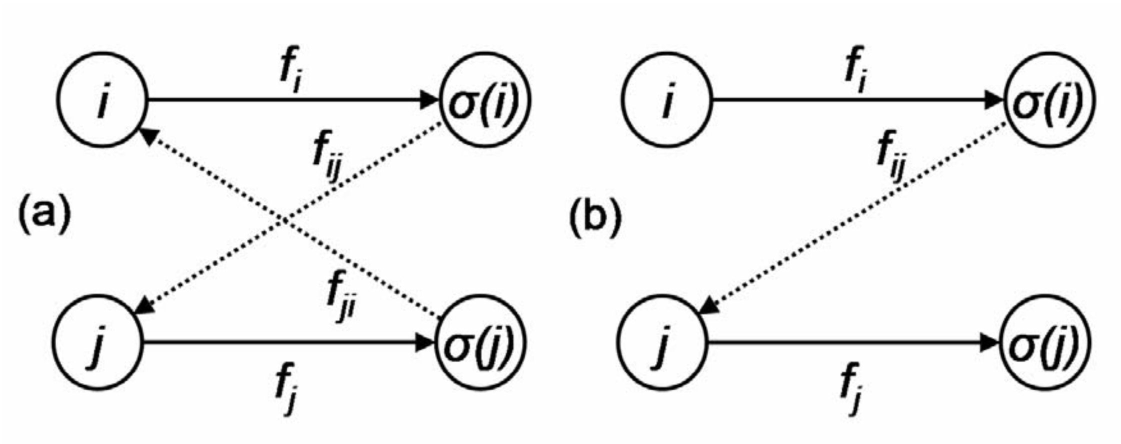

Figure 2: Two aircraft approaching one runway (a) and an ordering decision (b)

In Figure 3 (a-b), i and j are the operations corresponding to the entrance of two aircraft in an air segment (infinite capacity resource). When i precedes j (Figure 3 b) the separation constraint requires that the aircraft associated to j must respect the minimum separation constraint both at entrance and at the exit of the air segment: $t_j \geq t_i + f_{ij}$ and $t_{\sigma(j)} \geq t_{\sigma(i)} + f_{ij}$. For the sake of clarity, we assume in Figure 3 that entrance and exit separation constraints have the same weight.

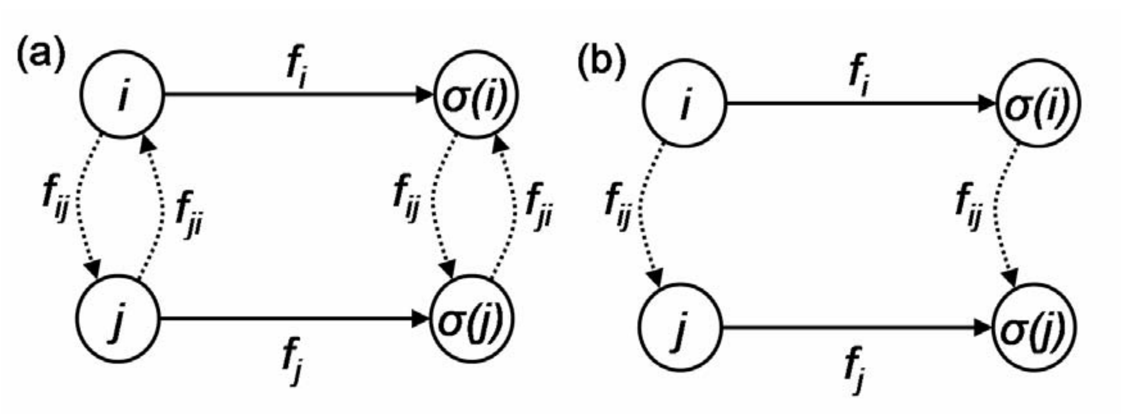

Figure 3: Two aircraft approaching one air segment (a) and an ordering decision (b)

Figure 4 (a) shows the formulation of holding circles on the alternative graph. Let *i* be the entrance of the aircraft in the holding and *σ(i)* the following operation. On the graph there is a pair of fixed arcs *(i, σ(i))* and *(σ(i), i)*, and one alternative pair. The length of *(i, σ(i))* is 0. The length of *(σ(i), i)*, instead, is *-β*, where *β* is the time to perform half circle. The alternative pair *((i, σ(i)), (σ(i), i))* with arc weight *β* and 0 respectively. Figure 4 (b) represents the selection of the holding circle while Figure 4 (c) the case with no holding circle.

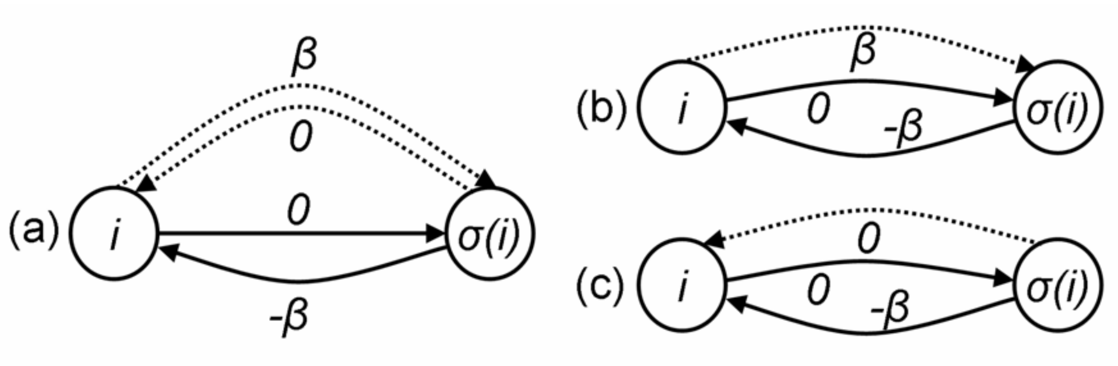

Figure 4: Formulation of the holding circle (a) and the cases in which is selected (b) or not selected (c)

EXAMPLES OF AIRCRAFT SCHEDULING AND ROUTING FORMULATIONS

Figure 5 shows a TMA scheme of the MXP airport in which there are two runways (RWY 35L, RWY 35R), which can be used for departing or landing aircraft. The airport resources are 3 airborne holding circles (TOR, MBR and SRN, numbered 1-3), 11 air segments for landing procedures (4-14), two runways (16-17) and a common glide path (15). The latter resource includes two parallel air segments before the two runways for which, besides a minimum longitudinal distance between aircraft, traffic regulations also impose a minimum diagonal distance.

The alternative graph of Figure 5 shows a take-off aircraft (C) and two landing aircraft (A and B). Each aircraft lies through a given route (air segments, holding circles and runways) and overtaking is not allowed within an air segment in the TMA. Each node of the graph represents the start time of an operation, e.g., A10 is aircraft A entering air segment 10. Fixed (alternative) arcs are depicted with solid (dotted) arrows. The realise time is modelled by a fixed arc from node 0 to the first operation of the job (e.g., arc (0, A1)).

On air segments, minimum and maximum traversing times are given for each aircraft, depending on its specific speed characteristics. The [min,max] constraint can be represented in *G* with a pair of conjunctive arcs: for each fixed arc related to a pair (aircraft, air segment) there is a fixed reverse arc. For example, aircraft A has a minimum traversing time (A10, A13) and maximum traversing time (A13, A10) on air segment 10. The violation of this constraint corresponds to a positive length cycle in *G*. With this formulation, each aircraft has a set of speed profiles limited by the [min,max] constraint. For example, alternative speed profiles can be used in order to analyze energy consumption, noise and/or pollution.

The minimum separation time between aircraft in the same air segment is modelled as a sequence dependent setup time. E.g. for aircraft A and B on air segment 4 we have the following two alternative pairs: ((A15, B15), (B17, A16)) and ((B15, A15), (A16, B17)). In a feasible solution, the order at the entrance must be equal to the order at the exit (e.g. the selection of arcs: entrance order (A15, B15) and exit order (A16, B17)), otherwise there is a positive lenght cycle in the graph.

The presence of aircraft on a runway imposes that no other aircraft can use it and thus the runway is a blocking resource (see, the alternative pair ((Bout, C17), (Cout, B17)). The order between aircraft of different categories has impact in the required minimal safety distance (e.g. the selection of arc (Cout, B17) requires the satisfaction of the required distance when C proceeds B). Note that, according to ICAO's classification, the distance between heavy and light aircraft is much larger when light aircraft follow heavy aircraft than vice versa.

Once an aircraft enters an airborne holding circle, it must fly at a given speed and can leave the holding circle only after the traversing of at least half length of the circle. The two alternative decisions are formulated with two fixed arcs and a pair of alternative arcs. For example, the two fixed arcs for aircraft B are the solid arrows (B3, B8) and (B8, B3) with weights *0* and $-\beta$. The pair of alternative arcs for aircraft B is ((B3, B8), (B8, B3)), weighted β and *0* and depicted with dotted arrows. In a solution, one of the two alternative arcs must be chosen.

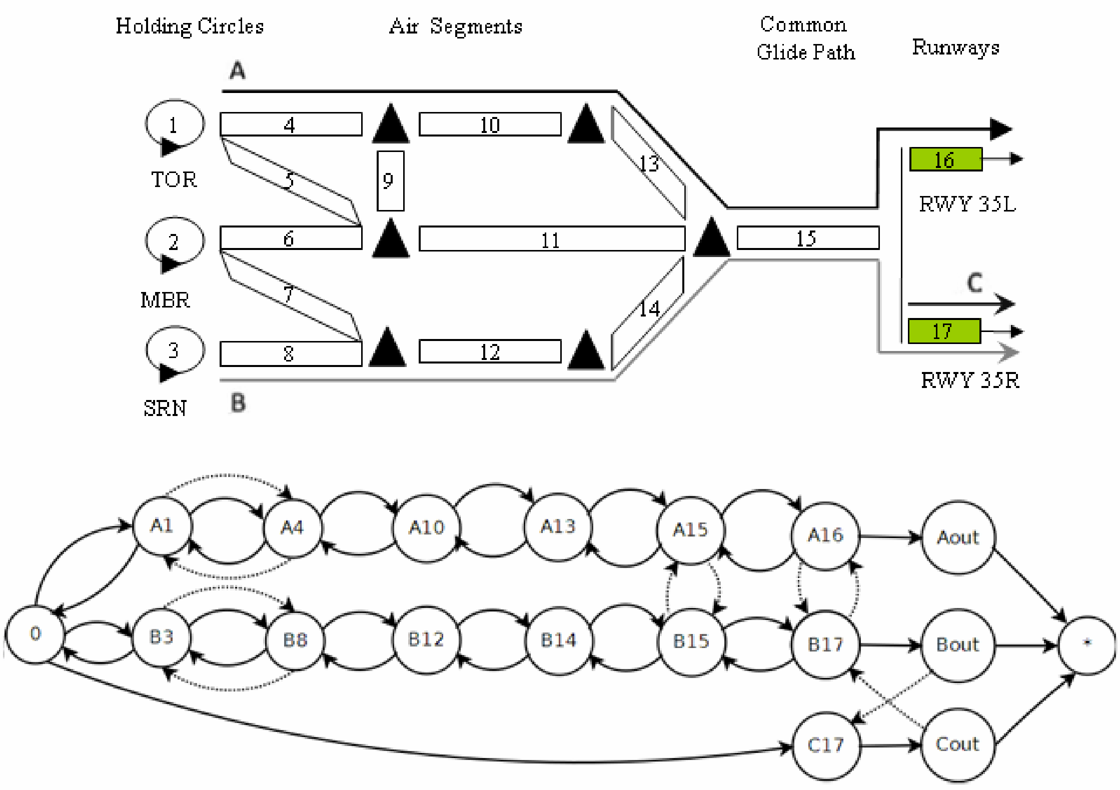

Figure 5: Example of alternative graph formulation of the ACDR problem

In our model landing aircraft have a deadline at the beginning of their processing. A deadline constraint is represented by a fixed arc from the first operation of the job to node 0 (arcs (A1, 0) and (B3, 0)). Deadline arcs have the same weight, with opposite sign, of the release time. Consequently, each landing aircraft must start its processing exactly when it appears at an entry fix of the TMA, and it can not be delayed at its entrance. This feature is close-fitting with the real operative procedures managed by the TMA controllers. Departing aircraft have not entrance constraints but they are penalized in the objective function in case of late traversing of the runway, and this is achieved with the insertion of due date arcs. This due date is modelled by a fixed arc from the last operation of the job to node * (arc (Cout, *)). Also for landing aircraft, we measure the objective function when they leave the associated runway.

For the default routes of Figure 5, there are potential conflicts between A and B at the common glide path and between B and C at the runway 17. Figure 6 shows a ACDR solution with default routes.

The solution of Figure 6 is obtained by scheduling aircraft A before than aircraft B on the resource 15 (selecting the alternative arcs (A15, B15) and (A16, B17)), while aircraft C is scheduled first on the runway 17 (selecting the alternative arc (Cout, B17)). We assume that aircraft A does not run any airborne holding circle (selecting the alternative arc (A4, A1)). Differently, aircraft B runs a half circle of weight β (selecting the alternative arc (B3, B8)) in order to avoid the potential conflict with aircraft A on the resource 15.

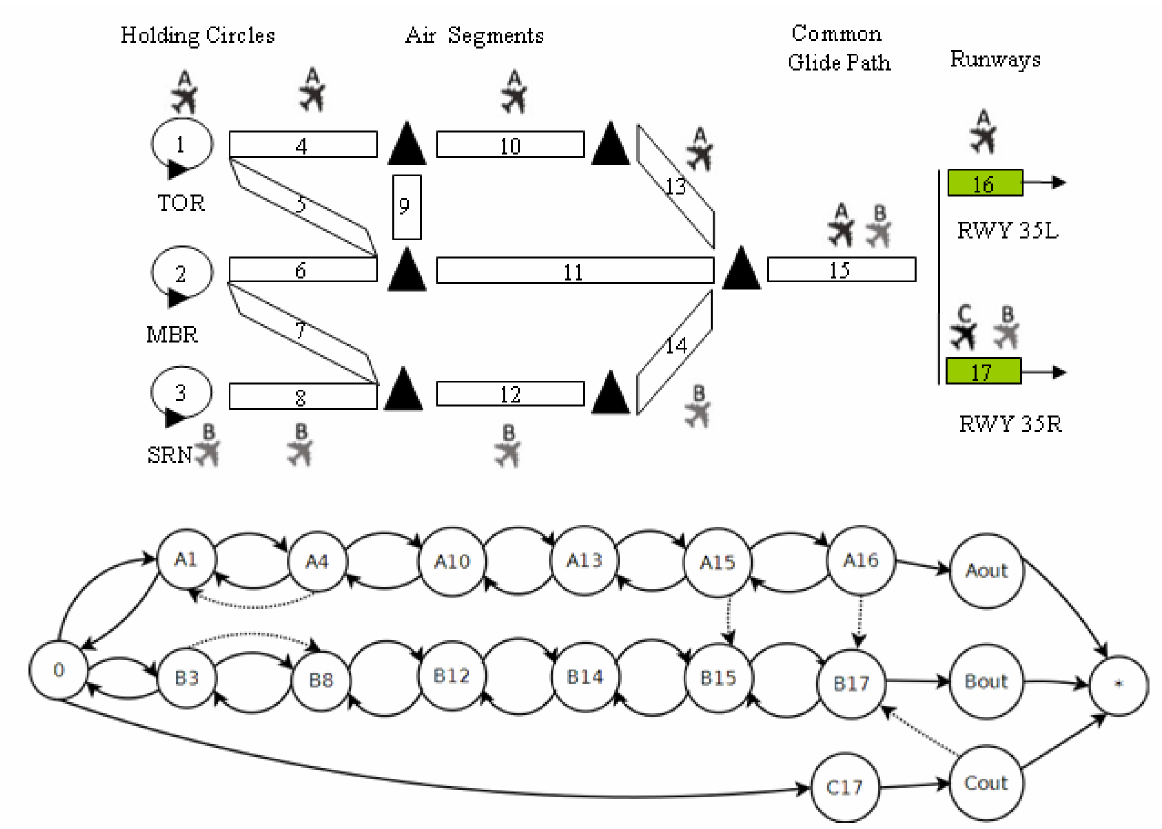

Figure 6: ACDR solution with default routes

Figure 7 shows a feasible schedule for the alternative graph *G' = (N', F', A')* for which the routes of A is modified in air. In the new graph, there is still a potential conflict between aircraft A and B at the resource 15. But now A has a longer route and B is scheduled before A on the common glide path. Aircraft C is still scheduled before B. Nor A and B need to travel holding circles.

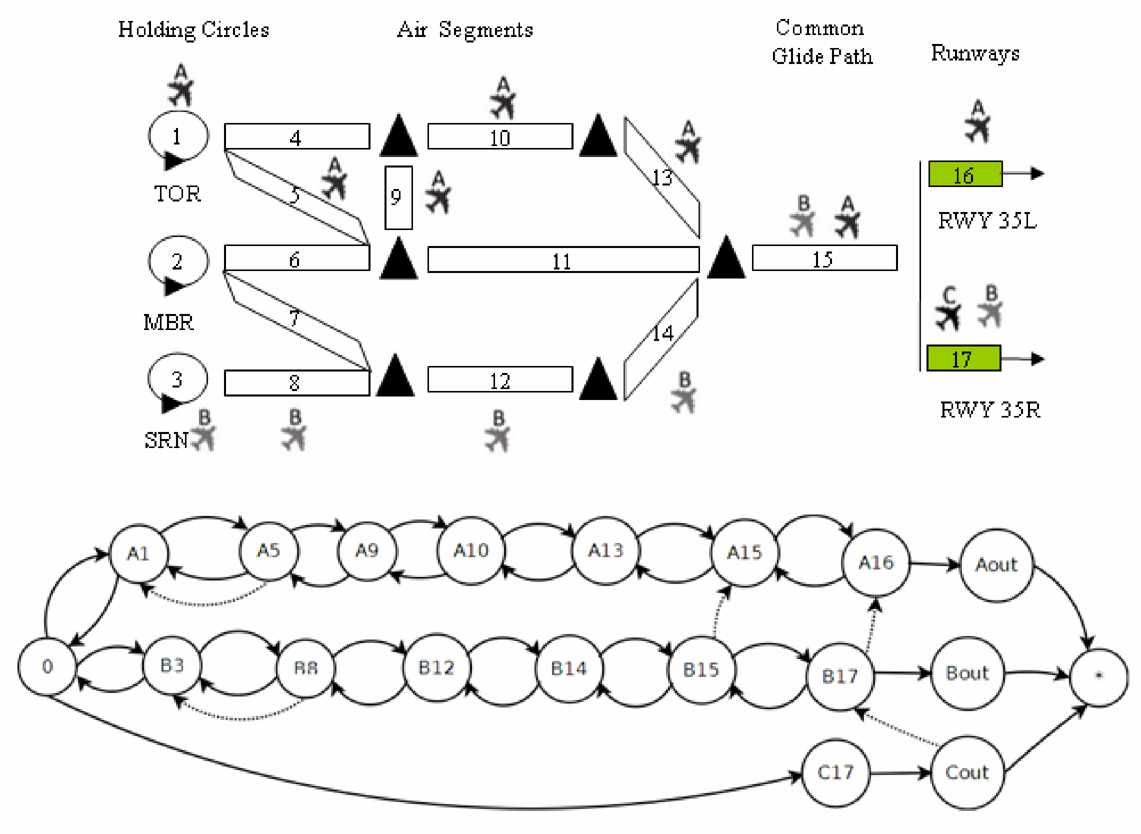

Figure 7: New ACDR solution with a different route for aircraft A

DESCRIPTION OF THE DISTURBANCE SCENARIOS

We tested the decision support system on a laboratory environment using real data of the Malpensa airport. The experiments are executed on a processor Intel i7 (2.84 GHz), 8 GB Ram and Linux operating system. The algorithms are implemented in the AGLibrary, developed by the "Aut.Or.I." Research Group of Roma Tre University. Each algorithm, we fixed a maximum computation time of 120 seconds.

Table 1 presents the 80 disturbance scenarios we use to test the ACDR algorithms. Each row reports average data over 20 instances. Column 1 shows four time horizons of traffic prediction, Column 2 the number of arriving/departing aircraft, Columns 3-5 the average number of nodes ($|N|$), of fixed arcs ($|F|$) and of alternative pairs ($|A|$). Columns 6-7 give the maximum and average entrance delays (in seconds). For each time horizon, we randomly generated 20 entrance delays in the TMA, simulating disturbed traffic conditions. We only delay aircraft that enter the network in the first half of each time horizon under study. Entrance delays are considered in the release (and eventually deadline) time of each aircraft and are introduced in the system prior the resolution of the ACDR problem. Columns 8-10 show the routes considered for each time horizon. At the Malpensa TMA, we consider three types of routes: the Combined one (aircraft can change route in air and runway), the Air one (aircraft can change the route in air only), and the Runway one (aircraft can change the runway they use, not their route in air). Both landing and departing aircraft can be rerouted, but the departing aircraft are rerouted on the runways only.

Table 1: Information on the disturbance scenarios for each time horizon of traffic prediction

Time Horiz	Land/Dep Aircraft	$\|N\|$	$\|F\|$	$\|A\|$	Max Entrance Delay	Avg Entrance Delay	Aircraft Routes		
							C	A	R
15	6/5	51	336	121	450	118.9	34	17	22
30	13/6	107	1297	546	900	252.5	70	35	38
45	19/13	155	2382	1044	1350	333.1	116	58	64
60	23/16	187	3393	1519	1800	460.6	138	69	78

EXPERIMENTAL RESULTS

This section compares the results obtained by the best TS with the performance of the scheduling solutions computed by BB with default routes. Both the algorithms have an execution time of 120 seconds. The comparison between TS and BB shows how rerouting alternatives, combined with aircraft retiming, can be used to get better performance than the default routes.

Table 2 shows the results for the Malpensa instances implemented with the alternative graph formulation. Column 1 reports the algorithm tested, BB with default routes and TS with rerouting alternatives. We indicate TS(c) for the combined rerouting, TS(a) for the air rerouting and TS(r) for the runway rerouting. Column 2 gives the time horizon for the instances, each row gives the average over 20 instances. Columns 3-7 present the maximum/average consecutive/total delays (in seconds), and the number of delayed aircraft. Column 8 reports the value of Delta Travel Time Spent (DTTS), in seconds. For an aircraft *a* arriving/departing at/from a runway *r*, DTTS is equal to t_{ar}-τ_{ar}, where τ_{ar} is the earliest possible time of *a* at *r* compatible with its current position and t_{ar} is its actual time at *r* in the schedule. This indicator is an interesting factor for energy consumption assessment.

In Table 2, the three kinds of rerouting outperform the BB values for all the time horizons. TS(c) is often the best configuration. Compared to BB, TS(c) achieves an improvement on the maximum consecutive delay minimization by 65% for 15-minute instances, by 34% for 30-minute instances, by 46% for 45-minute instances and by 51% for 60-minute instances. The other indicators are improved too. Regarding the other configurations, TS(r) obtains similar results to TS(c) for 30-minute, 45-minute and 60-minute instances, while TS(a) is often outperformed by the other tabu search configurations.

Table 2: Computational results on the BB and TS algorithms

ACDR Algo	Time Horiz	Max Cons Delay (s)	Avg Cons Delay (s)	Max Tot Delay (s)	Avg Tot Delay (s)	Delayed Aircraft	Total DTTS (s)
BB	15	64.4	7.0	147.7	19.4	1.4	710.6
TS(c)	15	22.7	2.3	118.1	13.7	1.4	614.5
TS(a)	15	24.9	2.6	118.2	13.8	1.4	592.7
TS(r)	15	60.9	6.63	136.8	17.9	1.8	725.4
BB	30	139.1	24.1	658,9	120.1	5.8	1832
TS(c)	30	91.6	12.6	622.0	107.3	6.5	1586.7
TS(a)	30	127.8	22.1	654.6	115.2	7.4	1868
TS(r)	30	94.9	14.1	634.6	108.8	6.8	1671.8
BB	45	305.9	61.6	1226.8	253.4	13.2	3646.4
TS(c)	45	166	35.9	1086.6	200.6	13.5	2987.8
TS(a)	45	234.9	57.9	1125.2	229.8	14.9	3645.9
TS(r)	45	170.7	31.6	1104.3	200.0	13.2	2900.6
BB	60	615.9	134.3	1835.5	432.0	23.8	2721.5
TS(c)	60	303.6	106.5	1714.8	388.4	24.7	6056.8
TS(a)	60	345.2	113.0	1745.0	404.4	24.5	6445.6
TS(r)	60	314.5	153.8	1704.1	378.5	23.5	5976.1

From previous experiments on the Malpensa and Fiumicino airports [22, 27], the BB procedure with default routes achieved an average reduction of more than 37% of the maximum consecutive delay compared to FIFO (First In First Out) with default routes. Such heuristic can be reasonably considered to be the scheduling rule used by air traffic controllers ([5]).

CONCLUSIONS

This paper investigates the potential of optimal aircraft rerouting for solving the ACDR problem. Computational results for the MXP airport demonstrate the effectiveness of our tabu search algorithm. TS is able to compute optimized aircraft timing and routing, including aircraft rerouting in air segments and runways. TS solutions are compared with the ones computed by BB with default routes. TS often outperforms BB in finding better quality solutions for the ACDR problem, also for large time horizons. Results on the MXP airport show that it is possible to obtain good solutions by combining rerouting on runways and air segments. However, runways are the most critical resources of the ACDR problem, specially for seriously disturbed traffic situations and dense traffic in the TMA.

Ongoing research is dedicated to the development of on-line decision support systems for air traffic control at TMAs and ATFMs. The rerouting strategies presented in this work should be part of the system core. Specific research directions may consider the extension of our methodology to better deal with aircraft trajectory variations in the landing/departing procedure. Another interesting research topic regards the assessment of traffic control measures in presence of even more disturbed traffic situations [23].

ACKNOWLEDGEMENTS

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