Optimal aircraft scheduling and routing at a terminal control area during disturbances

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ABSTRACT

This paper addresses the real-time problem of aircraft scheduling and routing. A main task of traffic controllers is to mitigate the effects of severe traffic disturbances on the day of operations in the Terminal Control Area (TCA) of an airport. When managing disturbed take-off and landing operations, they need to minimize the delay propagation and, in addition, to reduce the aircraft travel time and energy consumption. The paper tackles the problem of developing effective decision support tools for air traffic monitoring and control in a busy TCA. To this purpose, centralized and rolling horizon traffic control paradigms are implemented and compared. The mathematical formulation is a detailed model of air traffic flows in the TCA based on alternative graphs, that are generalized disjunctive graphs. As for the aircraft scheduling and (re-)routing approaches, the First In First Out (FIFO) rule, used as a surrogate for the dispatchers behaviour, is compared with various optimization-based approaches including a branch and bound algorithm for aircraft scheduling with fixed routes, a tabu search algorithm for aircraft re-routing, and a mixed integer linear programming formulation for simultaneous scheduling and routing. Various hypothetical disturbance scenarios are simulated for a real-world airport case study, Milano Malpensa, and the proposed timing and routing approaches are compared in terms of their performance in the different scenarios. The disturbed traffic situations are generated by simulating multiple delayed landing/departing aircraft and a temporarily disrupted runway. In general, the optimization approaches are found to improve the solutions significantly compared to FIFO, in terms of aircraft delay minimization. However, there are some trade-offs involved in picking the right approach and paradigms for practical implementations.

Keywords: Air Traffic Control; Disruption Management; Aircraft Scheduling and Routing; Disjunctive Formulation; Centralized and Rolling Horizon Frameworks.
1 Introduction

An increasing problem that air traffic controllers have to face is the growth of traffic demand while the availability of new airport resources is very limited. Aviation authorities are thus seeking methods to better use the infrastructure and to better manage aircraft movements in the proximity of airports, improving aircraft punctuality and respecting all safety regulations [25].

This paper deals with the development of advanced optimization approaches for improving the real-time management of severely disturbed aircraft operations at busy airports. Terminal area operations are usually considered under the umbrella of Air Traffic Control (ATC) because they are managed by local airport controllers. From a logical point of view, ATC decisions in a Terminal Control Area (TCA) 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 an aircraft passing timing has to be determined in each air segment, runway and (possibly) holding circle. In practice, routing (i) and timing (ii) decisions in a TCA 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 while that of the whole process is to limit the propagation of disturbances across flight legs either due to aircraft, crew, or passenger considerations [3].

Decision Support Systems (DSSs) based on optimization may help to exploit at most the capacity available in a TCA during operations. The improvement of take-off/landing operations is an important factor related to the performance of the entire ATC system. However, ATC decisions are still mainly taken by human controllers with only a limited aid from automated systems [18, 20, 26]. In most cases, computer support only consists of a graphical view of the current aircraft position and speed. As a result, delays are not effectively limited during landing and take-off operations. The optimization-based DSS developed in this work may support controllers to dynamically exploit at most the capacity available in the TCA during severe disturbances and busy traffic.

Landing aircraft move along predefined routes from an entrance point in the TCA to a 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 types 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 point from the TCA 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 TCA 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 in terms of re-timing, re-ordering, re-routing and holding actions. A potential 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 in each TCA resource and the aircraft types (we consider three aircraft categories: small, medium and large).
The problem of reacting to disturbed traffic conditions is a key issue in air traffic control practice (see, e.g., [26, 32]). This paper focuses on the real-time control problem to provide optimal conflict-free airborne decisions at the TCA. Similar problems are also studied in railway transportation field for re-ordering and re-routing problems [14, 16, 25]. However, the two types of problems have a quite different structure and require careful adaptation of existing solution frameworks, mathematical models and algorithmic methods.

In previous works of our research group, we developed a branch and bound algorithm for the ATC-TCA problem with fixed routes, in which aircraft routes are decided at preliminary step [15]. In a recent work, we developed an iterative approach for solving the ATC-TCA problem with flexible routes [17, 16]. Given a route for each aircraft, a scheduling approach takes the aircraft sequencing decisions and assigns the start time to each operation. A re-routing approach then searches for better aircraft routes. From our previous research [16], a better performance has been observed when using runway re-routing compared to the re-routing of other TCA resources.

The objective of this work is to investigate the potential benefits of optimization-based solvers for the real-time aircraft scheduling and routing problem at a busy and complex TCA, in presence of severe disturbances and even for large time horizons of traffic predictions. To this aim, this paper presents a number of modelling and algorithmic contributions. The original contributions are the next summarized:

• A new formulation is proposed for the simultaneous aircraft scheduling and routing problem.

• The problem is solved via various solution approaches: 1. a commercial solver, 2. an optimization solver based on a problem decomposition in re-timing, re-ordering and re-routing variables, 3. a temporal decomposition of the overall problem, 4. a number of combinations of the proposed approaches. Specifically, the approach 2 is based on the algorithms developed by D’Ariano et al. [15, 17], and is extended in the current paper by means of a procedure to speed-up the search of a feasible schedule. The approach 3 was presented in Samà et al. [29]. Approaches 4 extend the latter approach to deal with routing flexibility.

• Three model variants are proposed to study different objective functions and user requirements.

• The three model variants and the various solution approaches are compared in the computational results section. We tested 80 practical ATC-TCA instances of the Milano Malpensa airport (including various sources of disturbance and traffic predictions of increasing length). Each instance has been tested for the three model variants and for the various solution approaches.

• The computational results show the high potential of the optimization-based approaches compared to the FIFO rule. The optimization procedures are evaluated in terms of computation time indicators, number of optimal solutions, number of constraint violations and aircraft delay minimization.

The paper is organized in five sections. Section 2 gives a brief literature review on aircraft scheduling and routing models related to the present work. Section 3 presents our
problem formulation via alternative graphs. Section 4 describes the approaches proposed to solve the problem. Section 5 provides a set of model variants, and describes the ATC-TCA instances and the computational results. The experiments are shown for various time horizons of traffic prediction with multiple delayed aircraft and a temporary disruption due to severe weather issues. Section 6 concludes the paper and outlines research directions dealing with the traffic control at busy TCAs.

2 Review of the related literature

The Aircraft Traffic Flow Management (ATFM) problem has been the subject of several studies on the development of mathematical formulations and heuristic/exact algorithms, see, e.g., [2, 3, 4, 5, 6, 7, 10, 19, 22, 24]. Recent studies on the ATFM problem are dedicated to the development of several components, e.g. ground-delay programs, airspace flow programs in large networks connecting multiple airports, en-route vectoring and speed adjustments. For these approaches, various kinds of irregular operations are investigated, including lack of critical resources (aircraft and crew members) in order to cover services [1, 11, 21]. Other research directions focus on a market for arrival and departure slots at airport [24, 9, 12].

In our view, the mathematical structure of prior works on the ATFM problem is similar to the ATC-TCA problem studied in this paper, even if the scope moves from planning to re-planning in real-time. The underlying problems can be broadly classified into two groups of formulations: basic or detailed.

In basic models, the characteristics of the airport infrastructure is simplified and the flight paths are often aggregated. The aircraft scheduling and routing problem of a TCA is often viewed as a runway scheduling problem. With a basic model (see, e.g., [2, 7, 30, 31]), the runway scheduling problem is typically formulated as a single/parallel machine scheduling problem. Most of the early papers on ATFM falls in this category and the choice is motivated by the fact that the runways are often the TCA bottleneck.

In detailed models, individual aircraft are managed on each relevant TCA resource. The aircraft scheduling and routing problem is viewed as a job shop scheduling, in which a job is a sequence of TCA operations and timing constraints related to an aircraft. With a detailed model (see, e.g., [5, 8, 15, 17]), additional constraints and problem characteristics can be included.

In general, basic models are more tractable than detailed models. They can be useful to get insights on the runway selection and the airport flow balancing. At the same time, they are less realistic, since potential conflicts are not detected and solved at the level of individual aircraft and TCA resources.

In this paper, the ATC-TCA 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 [8] by including additional real-world constraints, such as holding circles, time windows for aircraft travel times, multiple capacities of air segments and single capacity constraints at runways. A single capacity resource is also named a blocking resource, since there must be at most an aircraft at a time processed on this type of resource. This formulation allows accurate modelling of future air traffic flows on the basis of the actual aircraft positions and speeds, and safety constraints. In addition, we use the alternative graph to obtain a new Mixed Integer Linear Programming (MILP) formulation for the ATC-TCA problem,
including all scheduling and routing alternatives. The proposed approach is used to study severely disturbed traffic situations, such as multiple landing and/or departing delayed aircraft and temporarily disrupted runway.

3 Mathematical formulations

The ATC-TCA problem can be divided into two sub-problems: (i) the selection of a route for each aircraft and (ii) the scheduling decisions once the routes have been fixed for each aircraft. This section describes this problem decomposition approach via alternative graphs, including a numerical example. Then a mathematical (MILP) formulation is proposed for the overall problem, in which binary variables for route selection are introduced within the scheduling optimization model based on alternative graphs.

3.1 Alternative graph formulation of the aircraft scheduling problem

In our formulation of the ATC-TCA problem, an operation is the traversing of a resource by an aircraft. The sequence of operations of an aircraft represents its route. Once a route has been assigned to each aircraft (routing problem), the ATC-TCA problem is reduced to the Aircraft Scheduling Problem (ASP), which can be modelled via the alternative graph of [23].

An alternative graph is a triple \( G = (N, F, A) \), where \( N = \{s, 1, \ldots, n, t\} \) is a set of \( n \) nodes plus the two additional nodes \( s \) and \( t \), representing the start and the end operations of the schedule; \( F \) is a set of fixed arcs, representing precedence constraints between operations; and \( A \) is a set of pairs of alternative arcs, representing the possible alternative scheduling decisions. In a feasible schedule exactly one alternative arc for each pair has to be selected such that all problem constraints are satisfied.

Each node, except \( s \) and \( t \), is associated with the start of an operation \( kp \), where \( k \) indicates the aircraft and \( p \) the resource it traverses. The start time \( h_{kp} \) of operation \( kp \) is the entrance time of \( k \) in \( p \).

Each fixed arc \( (kp, kj) \in F \) has associated the weight \( w_{kp,kj}^F \) that represents a minimum time constraint between \( h_{kp} \) and \( h_{kj} \), i.e. \( h_{kj} \geq h_{kp} + w_{kp,kj}^F \), in other words the minimum time required by aircraft \( k \) to traverse resource \( p \) and arrive at the following resource \( j \).

The alternative pairs \( ((kp, dj), (ul, vi)) \in A \) model aircraft sequencing and holding decisions, each one with its associated weight \( w_{kp,dj}^A \) and \( w_{ul,vi}^A \), respectively. If alternative arc \( (kp, dj) \) is selected in a solution, the additional constraint \( h_{dj} \geq h_{kp} + w_{kp,dj}^A \) is inserted. Otherwise, alternative arc \( (ul, vi) \) is selected, and the additional constraint \( h_{vi} \geq h_{ul} + w_{ul,vi}^A \) is added.

A partial selection \( S \) is a set of arcs in \( A \) obtained by selecting at most one arc from each alternative pair in \( A \). A partial selection is feasible if the graph \( (N, F \cup S) \) does not contain positive weight cycles. Otherwise, some of the problem constraints are not satisfied in the schedule. A solution to the ATC-TCA problem is a complete feasible selection, i.e. a selection in which exactly one arc from each alternative pair in \( A \) is selected. Given a selection \( S \) and any two nodes \( kp \) and \( dj \), we let \( l^S(kp, dj) \) be the weight of the longest path from \( kp \) to \( dj \) in the graph \( (N, F \cup S) \). By definition, the start time \( h_{kp} \) of node \( kp \in N \) is the quantity \( l^S(s, kp) \), which implies \( h_s = 0 \) and \( h_t = l^S(s, t) \). Note
that if $S$ is a complete feasible selection, then $h_{kp}$ is a feasible start time of operation $kp$. If $S$ is a partial selection, then $h_{kp}$ is a lower bound on the start time of operation $kp$ in any complete feasible selection including $S$. In fact, adding arcs to the selection cannot decrease the value $h_{kp}$.

Given the operations $s$ and $t$, their start times $h_s$ and $h_t$ are used to model the objective function of the ATC-TCA problem as follows. Let $h_{kp}$ be the actual start time of aircraft $k$ in resource $p$, $\alpha_{kp}$ the scheduled start time and $\eta_{kp}$ the earliest possible start time. We define the total delay of $k$ in $p$ as $h_{kp} - \alpha_{kp}$. The total delay can be divided into:

- the unavoidable delay, which represents the delay that cannot be recovered by rescheduling the aircraft movements and is modelled as $\beta_{kp} = \max\{0, \eta_{kp} - \alpha_{kp}\};$

- the consecutive delay, which represents the delay required to solve potential aircraft conflicts and is modelled as $\gamma_{kp} = \max\{0, h_{kp} + w_{kp,w}\}.$

We minimize the maximum consecutive delay $\gamma_{kp}$ by fixing the weight of the fixed arc $(kp,t)$ equal to $-\alpha_{kp} - \beta_{kp}$. The minimization of the maximum consecutive delay can be expressed as $h_t - h_s$ (see equation 1). A feasible schedule $S$ is optimal if the longest path between $s$ and $t$ in the connected graph (i.e. $l_{\text{opt}}(s,t)$) is minimum over all the solutions [13]. This objective function is used to minimize the aircraft delay propagation, that is an important indicator in the real-time traffic control context. The maximum consecutive delay minimization is inspired on the makespan minimization, and it has the advantage to compute a more compact schedule compared to the minimization of the total consecutive delay.

The alternative graph of the ATC-TCA problem can be formulated as follows:

$$\min \ h_t - h_s \quad (1)$$

s.t.

$$h_{kj} - h_s \geq w_{s,kj}^{F_r} \quad \forall(s,kj) \in F_r \quad (2)$$

$$h_t - h_{kj} \geq w_{kj,t}^{F_d} \quad \forall(kj,t) \in F_d \quad (3)$$

$$h_s - h_{kj} \geq w_{kj,s}^{F_d} \quad \forall(kj,s) \in F_d \quad (4)$$

$$h_{kj} - h_{kp} \geq w_{kp,j}^{F_{HC}} \quad \forall(kp,kj) \in F_{HC} \quad (5)$$

$$h_{kp} - h_{kj} \geq w_{kj,p}^{F_{HC}} \quad \forall(kj,kp) \in F_{HC} \quad (5)$$

$$h_{kj} - h_{kp} \geq w_{kp,kj}^{A_{HC}} \quad \forall((kp,kj),(kj,kp)) \in A_{HC} \quad (6)$$

$$h_{kl} - h_{km} \geq w_{km,kl}^{A_{AS}} \quad \forall((km,kl),(kp,kj)) \in A_{AS} \quad (7)$$

$$h_{ko} - h_{kj} \geq w_{kj,ko}^{A_{RW}} \quad \forall((ko,kj),(kj,kp)) \in A_{RW} \quad (10)$$
Constraints 2 model the fixed release arcs \((s, kj) \in F_{rt} \subset F\). The weight \(w_{s,kj}^{F_{rt}}\) is the minimum (release) time to start processing operation \(kj\). A release arc \((s, kj)\) represents the earliest possible arrival time of aircraft \(k\) in resource \(j\).

Constraints 3 model the fixed due date arcs \((kj, t) \in F_{dt} \subset F\). The weight \(w_{kj,t}^{F_{dt}} = -\alpha_{kj} - \beta_{kj}\) is the scheduled (due date) time to start processing operation \(kj\). A due date arc \((kj, t)\) represents the scheduled arrival time of aircraft \(k\) in resource \(j\).

Constraints 4 model the fixed deadline arcs \((kj, s) \in F_{Dt} \subset F\). The weight \(w_{kj,s}^{F_{Dt}}\) is the maximum (deadline) time to start processing operation \(kj\). A deadline arc \((kj, t)\) represents the latest possible arrival time of aircraft \(k\) in resource \(j\).

Constraints 5 and 6 are used to formulate the holding circle resources. We recall that holding circles are used by traffic controllers to let arriving aircraft wait before the start of their landing procedure when the TCA is congested. Let \(kp/kj\) be the entrance/exit of aircraft \(k\) in/from the holding circle. Constraints 5 model the fixed arcs \((kp, kj)\) and \((kj, kp) \in F_{HC} \subset F\) of weights \(w_{kp,kj}^{F_{HC}} = 0\) and \(w_{kj,kp}^{F_{HC}} = -\phi\), where \(\phi\) is the time required to perform a circle. Constraints 6 model a pair of alternative arcs \(((kp, kj), (kj, kp)) \in A_{HC} \subset A\), of weight \(w_{kp,kj}^{A_{HC}} = \phi\) and \(w_{kj,kp}^{A_{HC}} = 0\). Selection an arc over the other models if a holding circle is performed or not. The formulation of multiple circles can be easily done in a similar way.

Constraints 7 and 8 are used to formulate the air segment resources. The travel time of an aircraft in the air segment must be included in a processing time range \([w_{min}, w_{max}]\). Let \(km/kl\) be the entrance/exit of aircraft \(k\) in/from the air segment. Constraints 7 model two fixed arcs \((km, kl)\) and \((kl, km) \in F_{AS} \subset F\) of weights \(w_{km,kl}^{F_{AS}} = w_{min}\) and \(w_{kl,km}^{F_{AS}} = -w_{max}\).

In each landing/departing air segment, air traffic regulations impose a minimal longitudinal and diagonal separation distance between consecutive aircraft, that varies according to the aircraft category (e.g. small, medium and large aircraft). Since an overtake between two aircraft \(k\) and \(u\) in the same air segment is not allowed for safety reasons, the entrance and exit orders between the aircraft must be the same. Constraints 8 model two pairs of alternative arcs that represent the minimum separation time between two aircraft in the air segment \(m\) as a sequence-dependent setup time: \(((km, um), (um, kl))\) and \(((um, km), (kl, un)) \in A_{AS} \subset A\). We observe that \(l\) and \(n\) are the successive resources for aircraft \(k\) and \(u\), respectively. The selection of the alternative pairs models the order in which the aircraft enter/exit the air segment.

Constraints 9 and 10 are used to formulate the runway resources as a blocking resource. Constraints 9 model the fixed arc \((kj, ko) \in F_{RW} \subset F\), of weight \(w_{kj,ko}^{F_{RW}}\) equal to the processing time of runway \(j\) by aircraft \(k\). Constraints 10 model a pair of alternative arcs \(((ko, uj), (ug, kj)) \in A_{RW} \subset A\), of weights \(w_{ko,uj}^{A_{RW}}\) and \(w_{ug,kj}^{A_{RW}}\) equal to the sequence-dependent setup time between aircraft \(k\) and \(u\) in runway \(j\). The selection of the alternative pair models the order in which the aircraft use the runway. We observe that \(o\) and \(g\) are the successive resources for aircraft \(k\) and \(u\), respectively.

A detailed illustration of the formulation for each specific TCA resource can be found in [17]. We next provide an illustrative example of the alternative graph formulation for a numerical case study.
3.2 A numerical example

Figure 1 presents a hypothetical traffic situation with three aircraft, two landing (A and B) and one departing (C), traversing the TCA of Milan Malpensa (MXP) airport. The TCA resources are: three airborne holding circles (named TOR, MBR and SRN, numbered 1-3); eleven air segments for landing procedures (numbered 4-14); two runways (named RWY 35L, RWY 35R, numbered 16-17), which can be used for aircraft departing and landing procedure; a common glide path (numbered 15). The latter resource is a special type of landing air segment in which traffic regulations impose a minimum diagonal distance between aircraft, in addition to a minimum longitudinal distance. Overtaking is permitted at triangular locations and runways, while it is forbidden within air segments in the TCA.

![Figure 1: A hypothetical traffic situation at the Milan Malpensa (MXP) airport](image)

The routes used for the three aircraft are the following. Aircraft A has two possible routes in the TCA. Its entrance point in the TCA is TOR (resource 1) and it can either process air segments 4, 10, 13, 15 and land on runway 16 (default route) or process air segments 5, 11, 15 and land on runway 17 (alternative route). Aircraft B and C, instead, have just one possible route. Aircraft B arrives from entry point SRN (resource 3), processes air segments 8, 12, 14, 15 and lands on runway 17, while aircraft C is a departing aircraft and takes-off from runway 16.

Figure 2 (a) shows the alternative graph formulation of this example when the default route is chosen for aircraft A. In the graph, each node models the start of an operation, e.g. node A4 represents aircraft A on resource 4. The default route for aircraft A is thus expressed by the following chain of nodes A1, A4, A10, A13, A15, A16, Aout, and associated start times. Similarly, for aircraft B (nodes B3, B8, B12, B14, B15, B17, Bout) and C (nodes C16, Cout). Fixed (alternative) arcs are depicted with solid (dotted and coloured) arrows. We assume that the start time of traffic prediction is $h_s = 0$.

We now model the default route of aircraft A in all its components. Applying the same logic, we also model the operations of aircraft B and C. Each arc weight represents time units. The fixed arc $(s, A1) \in F_{rt}$ is a release arc and its weight $w_{F_{rt}}^{s,A1} = 0$ is a release time, modelling the expected time at which aircraft A should enter the TCA from the entry point TOR. The fixed arc $(A1, t) \in F_{dt}$ is a due date arc and its weight $w_{F_{dt}}^{A1,t} = 0$ is a due date time, that allows us to measure the possible delay of aircraft A in entering the TCA.

Aircraft A can (possibly) wait in the holding circle resource before being guided into its landing sequence. The fixed and alternative arcs between nodes A1 and A4 depict how
Figure 2: Alternative graph for the default routes (a) and a solution (b)
Figure 3: Alternative graph with an alternative route for aircraft $A$ (a) and a solution (b)
holding circles are modelled. The weights \( w_{A_{1A_{4}}A_{4}}^{HC} = 0 \) and \( w_{A_{4A_{1}}A_{1}}^{HC} = -240 \) of the two fixed arcs \(((A_{1}, A_{4})\) and \((A_{4}, A_{1}) \in F_{HC})\) represent respectively the minimum and maximum time that can be spent by aircraft \( A \) in holding circle resource \( 1 \). Each alternative pair \(((A_{1}, A_{4}), (A_{4}, A_{1}) \in A_{HC})\) models a specific waiting time in the holding circle \((0, 180\) or \(240\)). Specifically, we have three alternative feasible situations: selecting arc \((A_{4}, A_{1})\) of weight \( w_{A_{4A_{1}}A_{1}}^{HC} = 0 \) and arc \((A_{4}, A_{1})\) of weight \( w_{A_{4A_{1}}A_{1}}^{HC} = -180 \) means 0 waiting time, selecting arc \((A_{1}, A_{4})\) of weight \( w_{A_{1A_{4}}A_{4}}^{HC} = 180 \) and arc \((A_{4}, A_{1})\) of weight \( w_{A_{4A_{1}}A_{1}}^{HC} = -180 \) means 180 waiting time, selecting arc \((A_{1}, A_{4})\) of weight \( w_{A_{1A_{4}}A_{4}}^{HC} = 240 \) and arc \((A_{1}, A_{4})\) of weight \( w_{A_{1A_{4}}A_{4}}^{HC} = 180 \) means 240 waiting time.

Once out of the holding circle resource, aircraft \( A \) processes a number of air segments. The travel time on each air segment is computed according to the speed profile of \( A \) and varies between minimum and maximum possible values, since the trajectory of each aircraft flying in the TCA must vary in a pre-defined window. This time window is modelled though a pair of fixed arcs. In particular, the minimum travel time of aircraft \( A \) on air segment 4 is given by the weight \( w_{A_{1A_{4}}A_{4}}^{AS} = 61 \) of the fixed arc \((A_{4}, A_{10}) \in F_{AS})\), while the maximum travel time is given by the weight \( w_{A_{1A_{4}}A_{4}}^{AS} = -65 \) of the fixed arc \((A_{10}, A_{4}) \in F_{AS})\), expressed as a negative value in the formulation. The processing of the other air segments is modelled in a similar way.

The last operation of aircraft \( A \) in the TCA is the landing operation on runway \( 16 \), depicted by using fixed arc \((A_{16}, A_{out}) \in F_{RW} \) of weight \( w_{A_{16A_{out}}}^{FRW} = 60 \). Also, in order to measure the possible consecutive delay of aircraft \( A \) at runway \( 16 \), a due date arc \((A_{16}, t)\) of weight \( w_{A_{16A_{out}}}^{FD} = -262 \) is used.

Having more than one aircraft scheduled in each TCA resource, potential conflicts between aircraft routes must be modelled and managed such that minimum separation times are always respected and consecutive delays are minimized. In Figure 2, aircraft \( A \) and \( B \) have a potential conflict on the common glide path (resource \( 15 \)), and, since an overtaking is not possible within any air segment (including resource \( 15 \)), the same sequencing decision must be taken at the entrance and exit of resource \( 15 \) between the two aircraft. This is modelled by two pairs of alternative arcs \(((A_{15}, B_{15}), (B_{17}, A_{16}))\) and \(((B_{15}, A_{15}), (A_{16}, B_{17})) \in A_{AS})\), weighted with the minimum separation times required at the entrance \( w_{A_{15B_{15}}A_{15}}^{AS} = w_{B_{15A_{15}}B_{15}} = 42 \) and exit \( w_{B_{17A_{16}}A_{16}}^{AS} = w_{A_{16B_{17}}B_{17}} = 42 \) of the air segment. The order in which the two aircraft enter resource \( 15 \) is given by which alternative arcs are selected. If alternative arc \((A_{15}, B_{15})\) is selected in a solution, then aircraft \( A \) enters the common glide path before \( B \). Consequently, alternative arc \((A_{16}, B_{17})\) must be selected, because the same order is required at entrance and exit, otherwise, the selection of alternative arc \((B_{17}, A_{16})\) would cause a positive weight circle in the graph. Instead, if arcs \((B_{15}, A_{15})\) and \((B_{17}, A_{16})\) are selected, \( B \) enters resource \( 15 \) before \( A \).

Another potential conflict exists in Figure 2 between \( A \) and \( C \) on runway \( 16 \). Since the runway is considered as a blocking resource, this conflict is modelled by the alternative pair \(((A_{out}, C_{16}), (C_{out}, A_{16})) \in A_{RW})\). The weight \( w_{A_{outC_{16}}A_{16}}^{RW} = w_{C_{outA_{16}}A_{16}} = 42 \) of arcs \((A_{out}, C_{16})\) and \((C_{out}, A_{16})\) represents the minimum separation time required between the processing of \( A \) and \( C \) on runway \( 16 \). Selecting one arc of the pair models the order in which the aircraft will use the runway, e.g. the selection of alternative arc \((A_{out}, C_{16})\) means that \( A \) is processed before \( C \) on the runway.

Figure 2 (b) reports the optimal solution the scheduling problem. Both aircraft \( A \) and \( B \) have no waiting time in the holding circle resources, \( A \) is scheduled before \( B \) in the common glide path, \( A \) is sequenced before \( C \) on runway \( 16 \). The maximum consecutive
Figure 4: Gantt diagrams: FIFO, optimal scheduling and optimal routing solutions
delay is 64, which is the delay aircraft \( C \) at resource 16.

Figure 3 (a) shows the alternative graph in which the alternative route for aircraft \( A \) is fixed. The new nodes of \( A \) are \( A1, A5, A11, A15, A17, Aout \). With the new route for \( A \), there is no more potential conflict between aircraft \( A \) and \( C \) on runway 16, however there is a new potential conflict between \( A \) and \( B \) on runway 17, which is modelled by the alternative pair \( ((Aout, B17), (Bout, A17)) \) \( \in A_{RW} \).

Figure 3 (b) presents the optimal solution of the ATC-TCA problem (with flexible routes). Neither \( A \) nor \( B \) have a waiting time in the holding circle resources, \( A \) is scheduled before \( B \) in the common glide path and on runway 17. The maximum consecutive delay is 0.

Figure 4 shows the Gantt diagram of the FIFO, the optimal scheduling, the optimal routing and scheduling solutions. Each diagram reports the following information: a dotted vertical line for each due date arc, a thick rectangle for the minimum processing time of each aircraft in each resource, a thin rectangle for the additional processing time of some aircraft in some resources (due to the resolution of potential conflicts). The critical path is highlighted in yellow colour. The overlapping rectangles model the situation in which multiple aircraft are assigned to the same air segment resources.

In the FIFO solution both aircraft \( A \) and \( B \) have no waiting time in the holding circle resources, \( B \) is scheduled before \( A \) in the common glide path (resource 15), and \( C \) is sequenced before \( A \) on runway 16. The maximum consecutive delay is 140, which is the delay of aircraft \( A \) at the runway (resource 16). Comparing the FIFO solution with the optimized solutions, the minimization of the maximum consecutive delay helps in finding more compact solutions, and thus to limit the propagation of delays to forthcoming aircraft.

### 3.3 Formulation of the aircraft scheduling and routing problem

We present a MILP formulation of the ATC-TCA problem that considers the scheduling and routing decisions simultaneously. This can be obtained from the alternative graph formulation, enlarging sets \( F \) and \( A \) in order to contain the fixed and alternative arcs related to all possible aircraft routes. Each fixed arc translates into a constraint, while each alternative pair into a pair of alternative constraints, introducing a binary variable representing the choice made. The start time of each operation is a non-negative real variable. In addition, a variable is adopted for each alternative route. The resulting formulation is:

\[
\min h_t - h_s \quad (11)
\]

\[
\text{s.t.}
\]

\[
h_{krj} - h_s + M(1 - y_{kr}) \geq w_{s,krj}^{Fr} \quad \forall (s, kr, j) \in F_{rt} \quad (12)
\]

\[
h_t - h_{krj} + M(1 - y_{kr}) \geq w_{krj,t}^{Fd} \quad \forall (kr, j, t) \in F_{dt} \quad (13)
\]

\[
h_s - h_{krj} + M(1 - y_{kr}) \geq w_{krj,s}^{Fd} \quad \forall (kr, j, s) \in F_{dt} \quad (14)
\]

\[
h_{krj} - h_{kxp} + M(1 - y_{kr}) \geq w_{krj,kxp}^{Fr} \quad \forall (kr, j, xp) \in F_{HC} \quad (15)
\]
\[ h_{krj} - h_{k rp} + M x_{krp,krj} + M (1 - y_{kr}) \geq w_{krp,krj}^{A_{HC}} \]
\[ h_{k rp} - h_{krj} + M (1 - x_{krp,krj}) + M (1 - y_{kr}) \geq w_{krp,krj}^{A_{HC}} \forall((k rp, krj), (krj, k rp)) \in A_{HC} \]

\[ h_{k r j} - h_{k r m} + M (1 - y_{kr}) \geq w_{k r m, k r j}^{F_{AS}} \forall( (k rm, k r m) ) \in F_{AS} \]
\[ h_{k r m} - h_{k r j} + M (1 - y_{kr}) \geq w_{k r j, k r m}^{F_{AS}} \forall( (k r j, k r m) ) \in F_{AS} \]

\[ h_{u i m} - h_{k r m} + M x_{k r m, u i m} + M (2 - y_{kr} - y_{ui}) \geq w_{k r m, u i m}^{A_{AS}} \]
\[ h_{k r l} - h_{u i m} + M (1 - x_{k r m, u i m}) + M (2 - y_{kr} - y_{ui}) \geq w_{u i m, k r l}^{A_{AS}} \forall((k rm, uim), (uin, krl)) \in A_{AS} \]
\[ h_{k r m} - h_{u i m} + M x_{u i m, k r l} + M (2 - y_{kr} - y_{ui}) \geq w_{u i m, k r m}^{A_{AS}} \forall((uin, krm), (krl, uim)) \in A_{AS} \]

\[ h_{k r o} - h_{k r j} + M (1 - y_{kr}) \geq w_{k r j, k r o}^{F_{RW}} \forall( (krj, kro) ) \in F_{RW} \]

\[ h_{u i j} - h_{k r o} + M x_{k r o, u i j} + M (2 - y_{kr} - y_{ui}) \geq w_{k r o, u i j}^{A_{RW}} \]
\[ h_{k r j} - h_{u i g} + M (1 - x_{k r o, u i j}) + M (2 - y_{kr} - y_{ui}) \geq w_{u i g, k r j}^{A_{RW}} \forall((kro, uij), (uij, krj)) \in A_{RW} \]

\[ \sum_{r=1}^{R_k} y_{kr} = 1 \quad k = 1, \ldots, Z \quad \forall((k rp, krj), (krj, k rp)) \in A_{HC} \]

\[ x_{krp,krj}^{krj,krp} \in \{0, 1\} \quad \forall((k rp, krj), (krj, k rp)) \in A_{HC} \]

\[ x_{k rm, u i m}^{u i m, k r l} \in \{0, 1\} \quad \forall((k rm, uim), (uin, krl)) \in A_{AS} \]

\[ x_{u i m, k r m}^{u i m, k r l} \in \{0, 1\} \quad \forall((uin, krm), (krl, uim)) \in A_{AS} \]

\[ x_{k r o, u i j}^{u i j, k r o} \in \{0, 1\} \quad \forall((kro, uij), (uij, krj)) \in A_{RW} \]

\[ y_{kr} \in \{0, 1\} \quad k = 1, \ldots, Z ; \quad r = 1, \ldots, R_k \]

Operations are represented by the triple aircraft, route and resource, e.g. operation k rp models the processing of aircraft k on resource p when using route r. The binary variable \( x_{krp,krj}^{krj,krp} \) models the scheduling decision on the alternative pair \( ((k rp, krj), (krj, k rp)) \); the binary variable \( y_{kr} \) models the possible selection of route r by aircraft k; the non-negative real variable \( h_{k rp} \) models the start time of operation k p for route r. Furthermore, Z is the number of aircraft, and \( R_k \) the number of routes for aircraft k. M is a very large constant, e.g. equal to the sum of all arc weights. The objective function in 11 is the same as in 1.

This big-M formulation can be seen as an extended version of the formulation with fixed route of Section 3.1, since scheduling and routing decisions are taken simultaneously. In particular, the fixed constraints 12, 13, 14, 15, 17, 19 correspond to the fixed constraints 2, 3, 4, 5, 7, 9 when aircraft k uses route r.

Constraints 16 are the MILP equivalents of the alternative constraints 6. In case of a single holding pattern, binary variable \( x_{krp,krj}^{krj,krp} \) models whether the holding circle procedure (modelled by operations k rp and krj) is performed \( x_{krp,krj}^{krj,krp} = 0 \) or not \( x_{krp,krj}^{krj,krp} = 1 \) by aircraft k when using route r.

Constraints 18 are the MILP equivalents of the alternative constraints 8. Binary variables \( x_{k rm, u i m}^{u i m, k r l} \) and \( x_{u i m, k r m}^{u i m, k r l} \) model the sequencing decisions in the air segment m between aircraft k with route r and aircraft u with route i. There are two feasible sequencing solutions. If \( x_{k rm, u i m}^{u i m, k r l} = 0 \) and \( x_{u i m, k r m}^{u i m, k r l} = 1 \) aircraft k enters and exits air segment m before aircraft u. Alternatively, if \( x_{k rm, u i m}^{u i m, k r l} = 1 \) and \( x_{u i m, k r m}^{u i m, k r l} = 0 \) aircraft u enters and exits air segment m before aircraft k.
Constraints 20 are the MILP equivalents of the alternative constraints 10. Binary variable $x_{krwuij}^{uigkrj}$ models the sequencing decision in the runway $j$ between aircraft $k$ when using route $r$ and aircraft $u$ when using route $i$. If $x_{krwuij}^{uigkrj} = 0$ aircraft $u$ follows $k$, otherwise if $x_{krwuij}^{uigkrj} = 1$ aircraft $k$ follows $u$.

Constraints 21 model the fact that an individual route has to fixed for each aircraft, e.g. if $y_{kr} = 1$ aircraft $k$ uses route $r$ among its set of $R_k$ routes.

The MILP formulation of the example of Figure 1 is shown in the paper appendix.

4 Solution methods

This section describes the approaches proposed to solve the aircraft scheduling and routing problem at a busy TCA. We use a commercial solver to solve the MILP formulation, and propose two kinds of decomposition frameworks based on optimization approaches developed by our research group. The problem decompositions are motivated by the fact that the studied aircraft scheduling and routing problem is very difficult to solve in real-time, specially for large time horizons and disrupted traffic situations.

A temporal decomposition, named rolling horizon framework, is proposed to divide the problem into time horizons of traffic predictions of a reasonable size. This approach is compared with the centralized framework, that solves the overall problem in one step. In this work, we assume that information is fully known for all approaches at time 0 of the traffic prediction (before the solvers begin solving the problem). In this way, the rolling horizon approach is consistent with the centralized approach.

A problem decomposition in aircraft scheduling and routing variables is also investigated. This approach is implemented in the solver AGLIBRARY, developed at Roma Tre University. The solver first computes a feasible scheduling solution based off-line routes, in order that the workload of the runways is well balanced and there are no conflicts at runways when aircraft are on time. Then, the solver searches for better routes and tries to remove potential conflicts by re-routing some aircraft.

The implications of selecting the MILP formulation or the decomposition approaches are the following. The optimal solution of the original problem can only be obtained by solving the MILP formulation. The decomposition approaches are proposed to compute good quality solutions in a short computation time.

In general, whenever a solver does not provide a feasible schedule, the infeasibility is reported to the human traffic controllers. They (in cooperation with the airlines) are asked to take some actions that the automated system is not allowed to take, such as re-routing some aircraft to another airport or changing the maximum time that aircraft can spend in the holding circles.

4.1 Scheduling and re-routing decomposition

Figure 5 illustrates AGLIBRARY’s architecture in case of flexible routes. The basic idea is to first compute an aircraft scheduling solution, given a route for each aircraft, and then search for better aircraft routing solutions. Whether a feasible schedule is found or not, an aircraft re-routing module verifies if new routes, leading to a potentially better solution, exist. For each changed aircraft route, the timing of the aircraft in the TCA is modified accordingly. Whenever re-routing is performed, the aircraft scheduling module
computes a new schedule of aircraft movements using the new routes chosen. The iterative procedure returns the best aircraft times, orders and routes after a stopping criteria is reached, i.e. a given time limit of computation is reached or there are no more aircraft routes available.

Figure 5: AGLIBRARY solver based on iterative aircraft scheduling and re-routing

At the first run of the iterative procedure, an aircraft scheduling module computes aircraft orders and times given a default (off-line) route for each aircraft. The aircraft scheduling problem is solved by heuristic and exact algorithms. As rule-based method, First In First Out (FIFO) is used, taking aircraft ordering decisions one at a time by assigning each conflicting resource to the first aircraft requiring it. This local rule requires no look-ahead control action. According to Bennell et al. [5], this is a commonly used rule, even if human controllers may adjust the FIFO sequence in order to recover possible infeasible decisions. As optimization method, the truncated branch and bound (BB) algorithm of D’Ariano et al. [15] is adopted to solve the ASP to near-optimality. In particular, a binary branching scheme is implemented in order to take one scheduling decision at a time. This is implemented by selecting an alternative pair \(((kp, dj), (ul, vi))\) \(\in A\) and branching on the arcs \((kp, dj)\) and \((ul, vi)\) of the pair. We branch with priority on the alternative pairs associated to the runway resources, i.e. on the set \(A_{RW}\). This strategy is motivated by the fact that the runways are often the most used resources of the TCA. In fact, all aircraft use those resources.

The algorithm used in this paper for the iterative scheduling and re-routing approach is the Tabu Search (TS) of D’Ariano et al. [16, 17]. In particular, the neighbourhood strategy used here explores a number of randomly chosen neighbours in a so-called ramified critical path, that is an extension of the classical critical path method. A neighbour
consists of locally changing the route of a single aircraft in order to avoid traversing a resource on the critical path. At each iteration, the best neighbour is chosen as the new reference routing solution. In case no potentially better solution is found on the critical path neighbourhood, the search alternates this neighbourhood strategy with a diversification strategy, which consists of changing at random the route of a set of aircraft at the same time. The parameters of the tabu search algorithm have been tuned in [16]. In the remaining of this paper we indicate with BB+TS the tabu search algorithm for the re-routing module combined with the BB algorithm for the scheduling module.

4.1.1 Deadline implications

This subsection describes some useful techniques to speed up our solution algorithms, developed in the areas of scheduling theory and constraint programming. The first concept we use is named implication [13]. The idea is to prove that, given a partial selection \( S \) and an unselected pair of alternative arcs \( ((kp,dj), (ul, vi)) \in A \), then no feasible schedule exist if arc \((kp,dj)\) is selected. In such case, we say that arc \((ul, vi)\) is implied by \( S \) and can be immediately added to \( S \) without the need for branching.

Implication rules are a key property to solve the scheduling problem to optimality (see, e.g., [13, 15]). Besides the implications used in [15], in this work we add a further implication rule particularly useful in the presence of deadline constraints, that we call deadline implication.

**Figure 6:** Example of alternative graph with a deadline arc

**Proposition 4.1.** Consider a graph \((N,F,A)\) with \( F \) containing deadline arcs and a selection \( S \). Let \((mn, s)\) be a deadline arc and \(((kp,dj), (ul, vi))\) an unselected alternative pair. If \(-w_{F_{mn,s}}^{D^*} < h_{kp}^{S} + w_{kp,dj}^{A} + l^{S}(dj,mn)\) then \((ul, vi)\) is implied by \( S \), since arc \((kp,dj)\) is forbidden in any feasible schedule including \( S \).

**Proof.** The result follows from the observation that the quantities \( h_{kp}^{S} \) and \( l^{S}(dj,mn) \) equal the weights of two (longest) paths from \( s \) to \( kp \) and from \( dj \) to \( mn \) respectively. These paths form a cycle with arcs \((kp,dj)\) and \((mn, s)\). From the hypothesis it follows that the weight of this cycle is \( h_{kp}^{S} + w_{kp,dj}^{A} + l^{S}(dj,mn) + w_{mn,s}^{F_{D^*}} > 0 \) and therefore the selection \( S \cup (kp, dj) \) is infeasible. \( \square \)

Figure 6 (a) shows an example of a small alternative graph with deadline arc \((km,s)\). In the example, given the empty selection \( S = \emptyset \) the start time \( h_{um} \) of node \( um \) is equal to the weight of the fixed arc \((s, um)\), i.e. \( h_{um} = w_{s,um}^{F_{st}} \). Hence, if \( w_{s,um}^{F_{st}} + w_{um,km}^{A_{AS}} > -w_{km,s}^{F_{D^*}} \) the cycle in Figure 6 (b) has positive weight, the infeasibility being caused by the violation
of the deadline constraint. If this is the case, in any feasible schedule the alternative arc \((um, km)\) is forbidden and its alternative arc \((kl, un)\) is implied.

We observe that proposition 4.1 specifies which alternative arc is forbidden in a feasible schedule, with the consequence that the other arc in the pair is implied by \(S\), e.g. arc \((kl, un)\) in the example in Figure 6. Therefore, if both arcs in an alternative pair are forbidden, no feasible schedule exists given the selection \(S\).

The following proposition is derived from constraint programming techniques applied to the job shop scheduling problem (see, e.g., [27, 28]). The idea is to define for each node \(kp \in N\) an interval \([h_{kp}, h_{kp}^{max}]\) of [minimum, maximum] start time for any complete feasible selection \(\hat{S} \supseteq S\). By definition, the interval associated to the start node \(s\) is \([0, 0]\) and \(h_{t}^{max} = +\infty\). For any other node \(kp \in N\) the value \(h_{kp}^{max}\) can be recursively defined as follows:

\[
h_{kp}^{max} = \min_{(kp, xy) \in F \cup S} \{h_{xy}^{max} - w_{kp, xy}\}. \tag{26}
\]

**Proposition 4.2.** Consider an alternative graph \((N, F, A)\) with \(F\) containing deadline arcs and a selection \(S\). Let \(h_{kp} = l^S(s, kp)\), and let \(h_{kp}^{max}\) be defined according to (26). In any complete feasible selection \(\hat{S} \supseteq S\), and for each node \(kp \in N\), it holds \(h_{kp} \leq l^S(s, kp) \leq h_{kp}^{max}\). Moreover, given an unselected alternative pair \(((kp, dj), (ul, vi))\), if \(h_{dj}^{max} < h_{kp} + w_{A}^{A} + w_{ul, vi}\) then arc \((kp, dj)\) is forbidden and \((ul, vi)\) is implied by \(S\).

**Proof.** The proof follows from Proposition 4.1. In fact, if \(h_{kp}^{max} < \infty\) holds for some node \(kp \in N \setminus \{s\}\) it follows that there is a path from \(kp\) to \(s\) of weight \(-h_{kp}^{max}\). Clearly, adding arcs in \(\hat{S} \setminus S\) to the graph \((N, F \cup S)\) cannot remove the previous path. Assume by contradiction that a complete feasible selection \(\hat{S} \supseteq S\) exists such that \(l^S(s, kp) > h_{kp}^{max}\). This means that in the graph \((N, F \cup \hat{S})\) there is a path from \(s\) to \(kp\) of weight \(l^S(s, kp)\) and a path from \(kp\) to \(s\) of weight \(-h_{kp}^{max}\), i.e. there is a positive weight cycle in the graph, a contradiction. Similarly, there is a positive weight cycle if arc \((kp, dj)\) is selected, and this concludes the proof. \(\square\)

### 4.1.2 Pre-processing procedure

Proposition 4.2 is used at the root node of our branch and bound algorithm or before executing a heuristic scheduling algorithm to reduce the cardinality of set \(A\) and to early detect the infeasibility on an ATC-TCA instance when the deadline constraints are incompatible with each other.

The pre-processing procedure starts with the computation of \(h_{kp}\) and \(h_{kp}^{max}\) for each node \(kp \in N\). Then, we consider all the alternative pairs \(((kp, dj), (ul, vi))\) \(\in A\) such that \(h_{dj}^{max} < +\infty\) or \(h_{vi}^{max} < +\infty\), and check whether one of the following three cases occurs:

- \(h_{dj}^{max} < h_{kp} + w_{A}^{A} + w_{ul, vi}\) and \(h_{vi}^{max} < h_{ul} + w_{ul, vi}\),
- \(h_{dj}^{max} < h_{kp} + w_{A}^{A} + w_{ul, vi}\) and \(h_{vi}^{max} \geq h_{ul} + w_{ul, vi}\),
- \(h_{dj}^{max} \geq h_{kp} + w_{A}^{A} + w_{ul, vi}\) and \(h_{vi}^{max} \leq h_{ul} + w_{ul, vi}\).

In the first case the instance infeasibility is detected. In the second [third] case \((ul, vi)\) is implied \([(kp, dj)\) is implied] and the values \(h_{kp}\) and \(h_{kp}^{max}\) are updated for each node.
$kp \in N$. The procedure is repeated until no new arc is implied or until an infeasibility is detected. If the pre-processing procedure ends with a feasible partial selection, a scheduling algorithm is called in order to select the remaining alternative arcs.

Figure 7 presents an example of this procedure. Aircraft $A$ and $B$ are two landing aircraft, each with a deadline arc on the first operation, bounding its entrance in the TCA. Each node $kp \in N$ is labeled with the values $(h_{kp}, h_{max}^{kp})$. Figure 7 (a) refers to the first phase of the procedure, when $h_{kp}$ and $h_{max}^{kp}$ are computed and $S$ is an empty selection. Figure 7 (b) shows the changes occurred during the second phase. The analysis of the alternative pair $((B_{15}, A_{15}), (A_{16}, B_{17}))$ leads to the implication of arc $(A_{16}, B_{17})$, since arc $(B_{15}, A_{15})$ would cause a positive weight cycle in the graph. Similarly, the analysis of the alternative pair $((A_{15}, B_{15}), (B_{17}, A_{16}))$ leads to the implication of arc $(A_{15}, B_{15})$, alternative of arc $(B_{17}, A_{16})$ causing another positive weight cycle. In both cases, the update of $h_{kp}$ and $h_{max}^{kp}$ for each node $kp \in N$ does not change any value and the procedure terminates with the partial selection $\{(A_{16}, B_{17}), (A_{15}, B_{15})\}$.
4.2 Temporal decomposition

The aircraft scheduling and routing problem can be solved via the following temporal decomposition, in which the overall time horizon of traffic prediction is divided into consecutive traffic forecast intervals, named look-ahead periods. This decomposition is implemented via the rolling horizon framework introduced by Samà et al. [29] for the aircraft scheduling problem formulated via alternative graphs. We next describe an extended version of this framework that deals with aircraft scheduling and routing variables.

Figure 8: Example of rolling horizon approach with two roll periods and three look-ahead periods

For a given time horizon of prediction, we use a set of look-ahead periods \( T_i \) with \( i = 1, \ldots, u \). The start time of each look-ahead period is set via a fixed roll period, i.e. a non-overlapping period between the previous and the next look-ahead periods. The roll periods themselves are non-overlapping with each other.

Given the predicted information on the current operational conditions, the rolling horizon mechanism computes a scheduling and routing plan periodically, one for every roll period. This iterative mechanism complicates the optimization aspect compared to a single solver execution, due to the partial overlap of consecutive look-ahead periods and to the operational constraints related to this transition.

The rolling horizon framework performs \( u \) iterations. At iteration \( i \), the current look-ahead period \( T_i \) is solved. At the next iteration \( i + 1 \leq u \), the new look-ahead period \( T_{i+1} \) is solved. The latter look-ahead period starts after the roll period \( T_i - T_{i+1} \). Figure 8 gives the structure of the rolling horizon framework in case of three look-ahead periods (T1,T2 and T3) and two roll periods (T1-T2 and T2-T3).

Figure 9 presents the flowchart of the proposed rolling horizon framework. The lengths of the time horizon of traffic prediction, the look-ahead periods and the roll periods are input data. At each iteration \( i \) of the procedure, we generate the current look-ahead period \( T_i \), taking into account the following two aircraft sets: the aircraft entering the TCA during the look-ahead period \( T_i \) plus the aircraft that have not yet completed their operations in the look-ahead period \( T_{i-1} \). For the latter set of aircraft, we compute the set of feasible routes as follows. An aircraft route is feasible for the look-ahead period \( T_i \) if the route includes the last operation performed by the aircraft in the look-ahead period \( T_{i-1} \). Then, the look-ahead period \( T_i \) is solved by a specific solver. If a feasible schedule is found and the end of the traffic prediction is not reached, the next look-ahead and roll
periods are set. The rolling horizon procedure lasts till the resolution of the overall time horizon, or till an infeasibility is found at an intermediate iteration.

The centralized framework can be seen as a special case of the rolling horizon procedure, where the length of the look-ahead period is the same as the one of the overall time horizon of prediction. In this case, a single look-ahead period is thus generated and the procedure performs a single iteration.

5 Experiments

This section presents the experimental assessment performed by using the different formulations, frameworks and algorithms of Sections 3 and 4. The test bed is the Milan Malpensa terminal control area (MXP). The experiments are executed on processor Intel Core 2 Duo E6550 (2.33 GHz), 2 GB of RAM and Windows XP operative system. The MILP formulation is solved by the IBM LOG CPLEX MIP 12.0 solver.

5.1 Model variants

This subsection presents the three model variants studied in this paper. We use them to study different objective functions and user requirements. Figure 10 illustrates the difference between the models for a landing aircraft. We next describe the general characteristics of each variant for landing and take-off aircraft.

Model 1 (M1) minimizes the maximum consecutive delay at the runways, that are the most utilized TCA resources and a runway delay may have an impact on the management
of ground resources. This is achieved by inserting a due date arc \((kj, t)\) measuring the delay of each landing/take-off aircraft \(k\) at the entrance of scheduled runway \(j\). The weight \(w_{Fdt}^{kj}\) is set as described in Section 3.

Model 2 (M2) is a modified version of M1 in which the maximum consecutive delay at the entrance of the TCA is also minimized. This is achieved by inserting a due date arc \((ki, t)\) measuring the delay of each landing aircraft \(k\) at the entrance of air segment \(i\). The weight \(w_{Fdt}^{ki}\) is set equal to \(-w_{Fdt}^{ki}\). We penalize a late entrance in the TCA, since it may have an impact on the management of neighbouring areas.

Model 3 (M3) is an extension of M2 with the introduction of a set of deadline constraints in order to model that landing aircraft may have a maximum possible delay before entering the TCA. This is achieved by inserting a deadline arc \((ki, s)\) constraining the start of operation \(i\) of each landing aircraft \(k\) to be up to a maximum time. The weight \(w_{Fdt}^{ki,s}\) is the maximum possible entry delay for aircraft \(k\). This additional constraint may represent a limited fuel availability. In other words, if a delayed aircraft enters the TCA within its maximum feasible entrance time, we assume that the solver can assign up to a given maximum number of holding circles in the TCA. Otherwise, the solver returns an infeasibility related to that aircraft and the traffic controller has to interact with the system by, e.g., reducing the maximum number of holding circles that can be performed by the aircraft in the TCA. In the computational experiments of this paper, the maximum possible entry delay for each landing aircraft has been fixed equal to the scheduled entrance time in the TCA plus 15 minutes.
5.2 Disruption formulation

The management of a temporary unavailable resource can be modelled in terms of alternative graphs via a fictitious job with suitable timing constraints related to the disrupted resource.

![Diagram](image)

Figure 11: Examples of modelling of a disruption via alternative graphs

Figure 11 shows the case of a runway $d$ disrupted in the deterministic time window $[\text{disruption start, disruption end}]$, and a departing aircraft $k$ (a similar example can be considered for a landing aircraft). The fictitious job of the disrupted runway is made by a start operation $dj$ and an end operation $do$. The necessary time constraints are the following: the duration of the disruption (modelled by arc $(dj, do)$ with $w^F_{RW} = \text{disruption end} - \text{disruption start}$), the start time of the disruption (modelled by release arc $(s, dj)$ with $w^F_{rt} = \text{disruption start}$), the end time of the disruption (modelled by deadline arc $(dj, s)$ with $w^F_{Dt} = -\text{disruption start}$). The scheduling of aircraft $k$ in runway $d$ requires to consider its temporary unavailability. This is modelled by the fictitious alternative pair $((do, kj), (ko, dj))$ with $w^A_{do,kj} = w^A_{ko,dj} = 0$. If arc $(do, kj)$ is selected, aircraft $k$ enters the runway after the end time of the disruption in any feasible schedule. If arc $(ko, dj)$ is selected, aircraft $k$ leaves the runway before the start time of the disruption in any feasible schedule. The latter constraint is forced by the deadline arc $(dj, s)$, since a start time of $h_{ko} > |w^F_{dj,s}|$ would cause the positive weight cycle $s - kj - ko - dj - s$ of weight $h_{ko} + w^F_{dj,s}$ in the graph.

5.3 ATC-TCA delay instances

The ATC-TCA instances considered in the experiments are taken from real aircraft routing and scheduling data collected for the Milano Malpensa TCA, in Italy. Disturbed traffic conditions are simulated in a given time period of traffic prediction. Three time horizons of different length are considered: 30 minutes, 60 minutes and 180 minutes. The entry delays are chosen randomly according to a uniform distribution and up to a given maximum value. These delays are generated each 15 minutes and are applied to 1 to 5 aircraft.
entering the network in the first half of the time horizon under examination. For each
time horizon, 20 ATC-TCA delay instances are analyzed: 10 light disturbances (the
random delays are up to 5 minutes), and 10 heavy disturbances (the random delays are
up to 15 minutes).

Table 1: Characteristics of the ATC-TCA delay instances of Milano Malpensa

<table>
<thead>
<tr>
<th>Time Horizon Length (min)</th>
<th>Tot Num of Landing/Take-off Aircraft</th>
<th>Avg Entry Delay (sec)</th>
<th>Max Entry Delay (sec)</th>
<th>Avg Num of Delayed Aircraft</th>
<th>Tot Num of Landing/Take-off Aircraft Routes</th>
<th>Avg Num of Landing/Take-off Aircraft Routes</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>14/6</td>
<td>40</td>
<td>441</td>
<td>3.3</td>
<td>28/6</td>
<td>2/1</td>
</tr>
<tr>
<td>60</td>
<td>23/16</td>
<td>63</td>
<td>530</td>
<td>7.5</td>
<td>46/16</td>
<td>2/1</td>
</tr>
<tr>
<td>180</td>
<td>69/48</td>
<td>103</td>
<td>637</td>
<td>36.5</td>
<td>318/96</td>
<td>4.6/2</td>
</tr>
</tbody>
</table>

Table 1 gives further information on the 60 ATC-TCA delay instances. Each row
reports average data over the 20 instances of a specific time horizon. Column 1 gives the
time horizon length (in minutes), Column 2 the number of landing and departing aircraft,
Columns 3–4 the average and maximum entry delays (in seconds), Column 5 the average
number of delayed aircraft (i.e. aircraft entering the network after their release time),
Columns 6 the total number of landing/departing aircraft routes given as input to the
solver, Column 7 the average number of routes generated for landing/departing aircraft.
The last two columns characterize the complexity of the routing problem. For the 30-
minute and 60-minute instances we prefer to limit the number of routing variables. This
is achieved by considering alternative routing decisions for landing aircraft at runways
only. In fact, a better performance of this kind of re-routing compared changing routes
in air segments has been observed in a previous work [16]. For the 180-minute instances
we enlarge the set of available routes in order to generate more difficult instances. In this
set of instances, the landing aircraft have routing variables both at landing air segments
and runways, while the departing aircraft have routing variables at runways, since we do
not include departing air segments in our formulations.

Table 2 presents a detailed illustration of the difference between the various sets of
ATC-TCA instances. Each row presents the average number fixed constraints (Column
4), alternative constraints (Column 5) and MILP variables (Columns 6–8) related to the
20 instances of a specific time horizon of traffic prediction (Column 1), type of problem
(Column 2) and model variant (Column 3). The model variants differ in terms of fixed
constraints, since different sets of due date and deadline arcs are used. The scheduling
problem presents a smaller number of fixed and alternative constraints compared to the
scheduling and routing problem, since one route per aircraft is modelled in the former
problem and all available routes of each aircraft are modelled in the latter problem. The
180-minute traffic predictions present a large increase of the number of alternative arcs,
since multiple routes are available for each landing and take-off aircraft.

5.4 Setting of the solvers

This subsection discusses the settings of the two solvers. Regarding the rolling horizon
framework, we fix the roll period to 10 minutes and the look-ahead period to 15 minutes,
since this is the best configuration obtained from a previous campaign of experiments.
Samà et al. [29] tested 180-minute instances of the MXP airport with similar aircraft
delays for a job shop scheduling model with fixed routing. The selection of the best
configuration was mainly based on the following performance indicators: the maximum consecutive delay minimization and the quickness to compute a feasible aircraft scheduling solution.

Table 3 shows the computation time (in seconds) used to test the various solution approaches. Each row refers to a specific time horizon of traffic prediction and presents the same total computation time for each approach (i.e. 120 seconds for 30-minute instances, 240 seconds for 60-minute instances, 720 seconds for 180-minute instances). For the rolling horizon approach, the time limit of computation to solve each look-ahead period is the same for all time horizons of traffic prediction, since we use a look-head period of fixed length. For both the centralized and rolling horizon approaches, we tuned the time limit of computation of BB in the BB+TS algorithm in order to obtain a feasible schedule for all instances.

Table 3: Time limit for each combination of the solution approaches

<table>
<thead>
<tr>
<th>Time Horizon Length</th>
<th>Centralized Framework</th>
<th>Rolling Horizon Framework</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BB</td>
<td>MILP</td>
</tr>
<tr>
<td>30 min</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>60 min</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>180 min</td>
<td>720</td>
<td>720</td>
</tr>
</tbody>
</table>
5.5 Computational results

This subsection presents the computational assessment on the three model variants (M1, M2 and M3) of Section 5.1. The models variants are solved by the two frameworks (centralized and rolling horizon) and the four approaches (FIFO, BB for scheduling with default routes, BB+TS for scheduling and re-routing, the MILP formulation for simultaneous scheduling and routing) of Sections 3 and 4.

The instances generated for each model variant are the 60 ATC-TCA delay instances of Section 5.3, plus the 20 ATC-TCA disruption instances generated as follows: we inserted a temporary disruption in the 20 ATC-TCA delay instances with 180-minute time horizon of traffic prediction. Specifically, runway 16 is disrupted in the time window $[t_0 + 60 \text{ min}, t_0 + 120 \text{ min}]$ (all aircraft have to be scheduled on the other runway available in that time window). This traffic disruption is modelled via the alternative graph of Section 5.2. For the 20 ATC-TCA disruption instances, we use the same time limit of computation shown in row 3 of Table 3 for each combination of the solution approaches (see Section 5.4).

This subsection is organized as follows. Section 5.5.1 compares the results obtained when using the optimization algorithms of AGLIBRARY with/without pre-processing for the models with deadline constraints. For each solution approach, Section 5.5.2 presents the computational results for the 60 ATC-TCA delay instances, while Section 5.5.3 shows the results for the 20 ATC-TCA disruption instances. A detailed comparison of the various solution approaches will be reported in terms of the following indicators:

- Optimality: this is the number of instances, out of 20 that were simulated, for which a specific approach was able to find the optimal solution for the ASP ($\text{Num Optim Sched}$) and for the ATC-TCA problem ($\text{Num Optim Rout}$). The value of the optimal ASP solutions is found by BB, while the value of the optimal ATC-TCA solutions is found by CPLEX.

- Computation time (in seconds): we use a number of indicators that are the average time ($\text{Avg Best}$) and maximum time ($\text{Max Best}$) required to find the best solution, plus the average total time ($\text{Avg Tot}$) and the maximum total time ($\text{Max Tot}$) required by a specific approach.

- Violation: this is the number of violations ($\text{Num Viol}$) of the deadline constraints related to the maximum possible entry delay of each landing aircraft in the TCA.

- Delay minimization (in seconds): the objective function is expressed in terms of the maximum consecutive delay minimization. Specifically, M2 and M3 measure this objective at the entrance resources of the TCA ($\text{Max Entry Delay}$) and at the runway resources ($\text{Max Runway Delay}$), while M1 measures this objective at the runway resources only. Furthermore, the maximum between Max Entry Delay and Max Runway Delay is reported as $\text{Max Max Delay}$. For each set of studied instances, the best value of the objective function of each model variant is reported in bold.
5.5.1 Results with/without pre-processing

The aim of this study is to assess the effectiveness of using the pre-processing procedure. Table 5.5.1 reports a computational analysis of the model variant with deadline constraints (M3). Each row gives the average results on the 20 ATC-TCA instances of a specific time horizon of traffic prediction (Column 1). As solution approaches, we compare the results with (On) and without (Off) pre-processing (Column 2) when using the centralized framework and the optimization algorithms of AGLIBRARY (Column 3).

Table 4: Assessment with/without pre-processing for the 30-,60-,180-minute delay instances

<table>
<thead>
<tr>
<th>Time Horizon (min)</th>
<th>Pre-processing</th>
<th>Approach</th>
<th>Num Optim Sched</th>
<th>Num Optim Rout</th>
<th>Avg Best (sec)</th>
<th>Max Best (sec)</th>
<th>Avg Tot (sec)</th>
<th>Max Tot (sec)</th>
<th>Objective Function (sec)</th>
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</thead>
<tbody>
<tr>
<td>30</td>
<td>Off BB</td>
<td>1</td>
<td>-</td>
<td>3.7</td>
<td>4.2</td>
<td>116.0</td>
<td>120.0</td>
<td>35.7</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Off BB+TS</td>
<td>17</td>
<td>11.0</td>
<td>228.1</td>
<td>240.0</td>
<td>40.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>On BB</td>
<td>2</td>
<td>-</td>
<td>3.3</td>
<td>3.5</td>
<td>115.8</td>
<td>120.0</td>
<td>35.7</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>On BB+TS</td>
<td>18</td>
<td>11.0</td>
<td>228.1</td>
<td>240.0</td>
<td>40.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>Off BB</td>
<td>1</td>
<td>-</td>
<td>1.3</td>
<td>2.3</td>
<td>228.1</td>
<td>240.0</td>
<td>40.7</td>
<td></td>
</tr>
<tr>
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<td>Off BB+TS</td>
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<td>207.8</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>On BB</td>
<td>2</td>
<td>-</td>
<td>7.3</td>
<td>131.0</td>
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<td>240.0</td>
<td>38.0</td>
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<tr>
<td>60</td>
<td>On BB+TS</td>
<td>12</td>
<td>71.9</td>
<td>208.1</td>
<td>240.0</td>
<td>40.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>Off BB</td>
<td>0</td>
<td>-</td>
<td>19.9</td>
<td>86.7</td>
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<td>720.0</td>
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<tr>
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<td>0</td>
<td>131.9</td>
<td>720.0</td>
<td>720.0</td>
<td>99.5</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>180</td>
<td>On BB</td>
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<td>-</td>
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<td>720.0</td>
<td>99.5</td>
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<tr>
<td>180</td>
<td>On BB+TS</td>
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<td>152.8</td>
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<td>720.0</td>
<td>75.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Assessment with/without pre-processing for the 180-minute disruption instances

<table>
<thead>
<tr>
<th>Pre-processing</th>
<th>Approach</th>
<th>Num Optim Sched</th>
<th>Num Optim Rout</th>
<th>Avg Best (sec)</th>
<th>Max Best (sec)</th>
<th>Avg Tot (sec)</th>
<th>Max Tot (sec)</th>
<th>Objective Function (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off BB</td>
<td>0</td>
<td>-</td>
<td>8.8</td>
<td>10.3</td>
<td>720.0</td>
<td>720.0</td>
<td>951.8</td>
<td></td>
</tr>
<tr>
<td>Off BB+TS</td>
<td>0</td>
<td>0</td>
<td>224.5</td>
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<td>720.0</td>
<td>957.6</td>
<td></td>
</tr>
<tr>
<td>On BB</td>
<td>0</td>
<td>-</td>
<td>10.5</td>
<td>16.3</td>
<td>720.0</td>
<td>720.0</td>
<td>951.8</td>
<td></td>
</tr>
<tr>
<td>On BB+TS</td>
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<td>0</td>
<td>203.3</td>
<td>706.9</td>
<td>720.0</td>
<td>720.0</td>
<td>954.0</td>
<td></td>
</tr>
<tr>
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<td>0</td>
<td>-</td>
<td>9.4</td>
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<td>720.0</td>
<td>720.0</td>
<td>953.8</td>
<td></td>
</tr>
<tr>
<td>Off BB+TS</td>
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<td>0</td>
<td>226.3</td>
<td>720.0</td>
<td>720.0</td>
<td>720.0</td>
<td>959.5</td>
<td></td>
</tr>
<tr>
<td>On BB</td>
<td>0</td>
<td>-</td>
<td>9.3</td>
<td>11.3</td>
<td>720.0</td>
<td>720.0</td>
<td>951.8</td>
<td></td>
</tr>
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<td>290.5</td>
<td>720.0</td>
<td>720.0</td>
<td>720.0</td>
<td>925.3</td>
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</tr>
<tr>
<td>Off BB</td>
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<td>-</td>
<td>161.1</td>
<td>488.0</td>
<td>720.0</td>
<td>720.0</td>
<td>1000.8</td>
<td></td>
</tr>
<tr>
<td>Off BB+TS</td>
<td>0</td>
<td>0</td>
<td>260.0</td>
<td>720.0</td>
<td>720.0</td>
<td>720.0</td>
<td>1027.7</td>
<td></td>
</tr>
<tr>
<td>On BB</td>
<td>0</td>
<td>-</td>
<td>156.2</td>
<td>472.3</td>
<td>720.0</td>
<td>720.0</td>
<td>1000.8</td>
<td></td>
</tr>
<tr>
<td>On BB+TS</td>
<td>0</td>
<td>0</td>
<td>207.3</td>
<td>720.0</td>
<td>720.0</td>
<td>720.0</td>
<td>1023.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 5 reports a computational analysis on the 20 ATC-TCA instances with temporary runway disruption, formulated via the addition of a fictitious job with deadline
constraints (see Section 5.2). Each row gives the average results obtained for a specific model variant. We compare the same algorithms of Table 5.5.1.

From the results of Tables 5.5.1 and 5, we have the following observations. The pre-processing procedure is useful to compute better quality solutions, since the case On always gives equal or better quality solutions that the case Off. The improvement is more evident for BB+TS that applies the pre-processing procedure at each run of the aircraft scheduling module. Also, one additional optimal solution for a 30-minute delay instance of M3 is found by BB+TS. However, the case On sometimes takes a slightly longer computation time to find the best solution. In the following subsection, we always use the case On for BB and BB+TS.

5.5.2 Results for the entry delays

Tables 6, 7 and 8 show the computational results for the 30-minute, 60-minute and 180-minute delay instances of Table 1. Each row of the tables presents average results over the 20 ATC-TCA delay instances of a time horizon of traffic prediction for a specific combination of model variant (M1, M2 and M3), framework (centralized and rolling horizon) and approach (FIFO, BB, BB+TS and MILP). We report the results obtained for each combination, except the MILP approach combined with the centralized framework for the 180-minute delay instances. In fact, the latter approach never obtained a feasible schedule for all those instances. As for the previous subsection, we assess the various combinations in terms of the indicators related to optimality, computation time, violations and delay minimization. We next discuss the results of Tables 6, 7 and 8 when comparing the 3 model variants, the 2 frameworks, and the 4 approaches.

The optimized solutions of the model variants differ in terms of the indicators related to the maximum consecutive delay minimization. By construction we have that the M1 solutions better minimize the maximum runway delay, while the M2 and M3 solutions better minimize the maximum entry delay. The traffic controllers should therefore consider that a trade-off exists between the two indicators, e.g. selecting a solution with smaller runways delays may cause a larger late entrance in the TCA for some aircraft.

Regarding the impact of the deadline constraints, there is no violation in all ATC-TCA solutions computed for the delay instances. However, when dealing with the 180-minute delay instances the best solutions are obtained for M3, in terms of the various delay indicators. For this set of instances, limiting the entry delay of the most delayed aircraft may help to minimize the maximum consecutive delay.

The selection of the most suitable framework depends on the type of instance. For the 30-minute and 60-minute delay instances, the centralized framework often offers the best results in terms of the objective function of the three model variants. A different trend is found for the 180-minute delay instances in which the rolling horizon framework outperforms the centralized framework.

The MILP approach is always the best solution approach. For the 30-minute and 60-minute delay instances, the MILP approach in the centralized framework computes 58/60 and 52/60 optimal solutions, while 57/60 and 44/60 optimal solutions are obtained by the MILP approach in the rolling horizon framework. For the 180-minute delay instances, the latter approach is always the best approach, however we have no information on the value of the optimal solutions.

The time to compute the best solution of the MILP approaches is always below 22
Table 6: Assessment for the 30-minute delay instances

<table>
<thead>
<tr>
<th>Approach</th>
<th>Num Optim Sched</th>
<th>Num Optim Rout</th>
<th>Avg Best (sec)</th>
<th>Max Best (sec)</th>
<th>Avg Tot (sec)</th>
<th>Max Tot (sec)</th>
<th>Num Viol</th>
<th>Max Max Delay (sec)</th>
<th>Max Entry Delay (sec)</th>
<th>Max Runway Delay (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Centralized Framework - Model Variant M1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FIFO</td>
<td>15</td>
<td>-</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0</td>
<td>114.1</td>
<td>106.7</td>
<td>36.2</td>
</tr>
<tr>
<td>BB</td>
<td>20</td>
<td>-</td>
<td>0.3</td>
<td>0.9</td>
<td>6.9</td>
<td>46.2</td>
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<td>116.0</td>
<td>116.0</td>
<td>14.9</td>
</tr>
<tr>
<td>BB+TS</td>
<td>-</td>
<td>19</td>
<td>13.9</td>
<td>118.0</td>
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<td>120.0</td>
<td>0</td>
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<td>83.6</td>
<td>1.6</td>
</tr>
<tr>
<td>MILP</td>
<td>-</td>
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<td>1.5</td>
<td>4.2</td>
<td>1.6</td>
<td>4.3</td>
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<td>75.9</td>
<td>1.1</td>
</tr>
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<td><strong>Rolling Horizon Framework - Model Variant M1</strong></td>
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<tr>
<td>FIFO</td>
<td>15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>114.1</td>
<td>106.7</td>
<td>36.2</td>
</tr>
<tr>
<td>BB</td>
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<td>-</td>
<td>-</td>
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<td>3.4</td>
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<td>0</td>
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<td>-</td>
<td>-</td>
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<td>4.5</td>
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<td>33.6</td>
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<td>1.1</td>
</tr>
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<td><strong>Centralized Framework - Model Variant M2</strong></td>
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<td></td>
</tr>
<tr>
<td>FIFO</td>
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<td>0.3</td>
<td>0.5</td>
<td>0.3</td>
<td>0.5</td>
<td>0</td>
<td>114.1</td>
<td>106.7</td>
<td>36.2</td>
</tr>
<tr>
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<td>-</td>
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<td>1.6</td>
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<td>0.2</td>
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<td>106.7</td>
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<td>3.3</td>
<td>3.5</td>
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<td>35.7</td>
<td>11.2</td>
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<td>-</td>
<td>5.0</td>
<td>5.8</td>
<td>5.0</td>
<td>5.8</td>
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<td>204.2</td>
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<td>720.0</td>
<td>720.0</td>
<td>0</td>
<td>75.7</td>
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<td><strong>Rolling Horizon Framework</strong></td>
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<tr>
<td>FIFO</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>208.5</td>
<td>158.2</td>
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<td>-</td>
<td>-</td>
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<td>0</td>
<td>113.4</td>
<td>66.8</td>
<td>111.9</td>
</tr>
<tr>
<td>BB+TS</td>
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<td>0</td>
<td>-</td>
<td>-</td>
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<td>67.8</td>
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<tr>
<td>MILP</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>388.3</td>
<td>499.1</td>
<td>0</td>
<td>25.7</td>
<td>15.6</td>
<td>20.5</td>
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</table>
seconds for the 30-minute delay instances, while up to around 240 seconds and 500 seconds are required for the 60-minute and 180-minute delay instances. Considering the time to compute good quality solutions, the MILP approach combined with the rolling horizon framework takes up to 11 seconds for 30-minute delay instances and up to 49 seconds for the 60-minute delay instances. This combination can thus be considered as applicable for the real-time management of practical-size instances.

Regarding the other approaches, BB+TS better minimizes the objective function of each model variant compared to BB and FIFO, but it is less competitive than the MILP approach. The FIFO rule is the fastest approach, however it is also the worst approach in terms of aircraft delay minimization.

5.5.3 Results for the entry delays plus a disrupted runway

Table 9 shows average results obtained for the 20 ATC-TCA 180-minute disruption instances. Some approaches are not reported for the following reasons. FIFO very often failed to compute a feasible schedule. The MILP approach in the centralized framework was never able to find a feasible schedule. The problem to compute a feasible schedule in presence of a disruption becomes more difficult than for the delay instances, since a runway is disrupted and all aircraft have to be scheduled in the only available runway. We next compare the results of the three model variants, the two frameworks and the feasible approaches in terms of the indicators related to optimality, computation time, violations and delay minimization.

Table 9: Assessment for the 180-minute delay instances plus the temporary runway disruption

<table>
<thead>
<tr>
<th>Approach</th>
<th>Num Sched</th>
<th>Num Rout</th>
<th>Avg Best (sec)</th>
<th>Max Best (sec)</th>
<th>Avg Tot (sec)</th>
<th>Max Tot (sec)</th>
<th>Num Viol</th>
<th>Max Delay (sec)</th>
<th>Max Entry Delay (sec)</th>
<th>Max Runway Delay (sec)</th>
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<td>BB</td>
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<td>-</td>
<td>10.5</td>
<td>16.3</td>
<td>720.0</td>
<td>720.0</td>
<td>19</td>
<td>956.1</td>
<td>605.0</td>
</tr>
<tr>
<td></td>
<td>BB+TS</td>
<td>-</td>
<td>0</td>
<td>203.3</td>
<td>706.9</td>
<td>720.0</td>
<td>720.0</td>
<td>19</td>
<td>958.3</td>
<td>642.1</td>
</tr>
<tr>
<td>Rolling Horizon Framework - Model Variant M1</td>
<td>BB</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>515.3</td>
<td>578.9</td>
<td>11</td>
<td>892.2</td>
<td>439.0</td>
</tr>
<tr>
<td></td>
<td>BB+TS</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>720.0</td>
<td>720.0</td>
<td>11</td>
<td>844.6</td>
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<td>MILP</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>458.1</td>
<td>655.2</td>
<td>10</td>
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<td>-</td>
<td>9.3</td>
<td>11.3</td>
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<td>951.8</td>
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<td>925.3</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>551.8</td>
<td>639.7</td>
<td>13</td>
<td>853.4</td>
<td>401.8</td>
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<tr>
<td></td>
<td>BB+TS</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>720.0</td>
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<td>770.9</td>
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<tr>
<td>Centralized Framework - Model Variant M3</td>
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<td>-</td>
<td>156.2</td>
<td>472.3</td>
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<td>-</td>
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<td>720.0</td>
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<td>0</td>
<td>1023.4</td>
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<td>-</td>
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<td>636.9</td>
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<td>908.0</td>
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<td>BB+TS</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>720.0</td>
<td>720.0</td>
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<td>-</td>
<td>504.9</td>
<td>595.6</td>
<td>0</td>
<td>910.0</td>
<td>411.6</td>
</tr>
</tbody>
</table>

From the computational results of Table 9, the M1 and M2 solutions present a number
of violations of the deadline constraints. However, a feasible schedule is always found for M3 by delaying different aircraft (i.e. by computing a different sequencing and routing solution) compared to the M1 and M2 solutions. Specifically, M2 has the best performance in terms of the Max Max Delay minimization at the cost of 11 violations. The maximum consecutive delay is often due to late arrivals at the only available runway resource.

For this set of instances, BB+TS with the rolling horizon framework outperforms the other approaches in terms of delay minimization, even if this combination requires the largest computation time.

6 Conclusions and further research

This paper investigates the potential of using optimization-based approaches as decision support for air traffic control at a busy TCA, including the management of strong traffic disturbances (such as multiple aircraft delays and a temporarily disrupted runway). Centralized and rolling horizon frameworks are evaluated on a Italian practical case study, i.e. Milano Malpensa (MXP). For both frameworks, we analyzed the performance of a commonly used rule (i.e. the FIFO rule), a branch and bound algorithm for aircraft scheduling, a tabu search algorithm for iterative aircraft scheduling and re-routing, and a new MILP formulation for simultaneous aircraft scheduling and routing. We also compared the performance of the various approaches for three model variants, with some differences in the objective function and in the set of constraints.

From the computational results on the MXP TCA case study, we obtained the following insights:

- The solutions obtained for the three model variants show that there is a trade-off between the minimization of the entry delays and the runway delays. The minimization of the former delays is necessary for optimizing the coordination with the management of neighboring areas, while the minimization of the latter delays is necessary for the minimization of the passenger/freight delays and the delays of ground operations. Another comparison of the model variants is shown in terms of deadline constraint violations. For the disruption instances, a further trade-off is quantified between limiting the number of violations and the maximum consecutive delay. The resolution of the various model variants may thus give support to the traffic controllers in order to take more informed decisions.

- In the centralized framework, several optimal solutions are computed for the MILP formulation when dealing with 30-minute and 60-minute delay instances. However, the 180-minute delay instances are never solved to optimality and no feasible schedule is obtained for the 180-minute disruption instances within the given computation time. This result is due to the large number of scheduling and routing variables in the 180-minute instances. Further research should be dedicated to the development of exact methods and good lower bounds for the latter type of instances.

- The rolling horizon framework is the most robust approach, since a feasible schedule is always obtained when using the proposed optimization-based approaches for all tested instances. Furthermore, when dealing with 180-minute instances the rolling horizon framework outperforms the centralized framework in terms of the objective function minimized by each model variant.
• MILP is the best approach for the 30-minute, 60-minute and 180-minute delay instances, either in the centralized or rolling horizon framework. Up to the 60-minute delay instances, the MILP approach in the rolling horizon framework always computes a feasible schedule within less than one minute, so this combination can be potentially used for real-time traffic control. However, BB+TS in the rolling horizon framework is the best approach for the 180-minute disruption instances. The optimization algorithms of AGLIBRARY are thus competitive with the MILP approach. This result is more evident for the instances with deadline constraints, for which AGLIBRARY uses the pre-processing procedure. Comparing the AGLIBRARY approaches, BB+TS often presents better results than BB, since the use of re-routing results to be an added value when optimizing the aircraft flows in the TCA.

• The poor results obtained by FIFO confirms that a potential improvement is achievable by adopting intelligent aircraft scheduling and routing techniques as decision support for traffic controllers. In fact, FIFO is not able to compute a feasible schedule for the disruption instances and is outperformed by all other approaches for the delay instances. Overall, an average improvement (in percentage) is of around 64%, 88% and 93% is obtained when using BB, BB+TS and MILP.

Ongoing research is dedicated to the study of closed-loop decision support systems for traffic control, in which the length of the roll and look-ahead periods changes dynamically and information is updated in real-time. Other research directions are dedicated to the development of more efficient/effective re-ordering and re-routing algorithms, and to the investigation of multi-objective optimization approaches.

References


APPENDIX

The appendix presents the MILP formulation of the simultaneous aircraft scheduling and routing problem for the example of Section 3. The variables used in the formulation are the following:

- $h_t$ is a non-negative real variable indicating the start time of the last operation;
- $h_{K,r,p}$ is a non-negative real variable indicating the start time of the node corresponding to the operation of aircraft $K$ on resource $p$ when using route $r$ (route 1 being the default (off-line) route);
- $x_{K,r,p}X_{i,j}Y_{g,l}Z_{m,n}$ is a binary variable associated with the alternative pair $((K,r,p), (Y,g,l, Z,m,n))$, where each triple $K,r,p$ indicates the node corresponding to the operation of aircraft $K$ on resource $p$ when using route $r$;
- $y_K$ is a binary variable indicating whether route $r$ is chosen ($y_{K,r} = 1$) or not by aircraft $K$ (specifically, $y_{K,1} = 1$ if the default route of aircraft $K$ is selected).

The value of $h_s$ is set to the start time of the first operation. For the numerical example, $h_s = 0$.

Minimize $h_t - h_s$

Subject To

Start time of source node:
$h_s = 0$

Fixed arcs for aircraft $A$:
$h_{A,1.out} - h_{A,1.16} - My_{A,1} \geq -M + 60$
$h_t - h_{A,1.16} - M y_{A,1} \geq -M - 262$
$h_{A,1.16} - h_{A,1.15} - M y_{A,1} \geq -M + 108$
$h_{A,1.15} - h_{A,1.16} - M y_{A,1} \geq -M - 133$
$h_{A,1.15} - h_{A,1.13} - M y_{A,1} \geq -M + 38$
$h_{A,1.13} - h_{A,1.15} - M y_{A,1} \geq -M - 63$
$h_{A,1.13} - h_{A,1.10} - M y_{A,1} \geq -M + 55$
$h_{A,1.10} - h_{A,1.13} - M y_{A,1} \geq -M - 63$
$h_{A,1.10} - h_{A,1.4} - M y_{A,1} \geq -M + 61$
$h_{A,1.4} - h_{A,1.10} - M y_{A,1} \geq -M - 65$
$h_{A,1.1} - h_{A,1.4} - M y_{A,1} \geq -M - 240$
$h_{A,1.4} - h_{A,1.1} - M y_{A,1} \geq -M$
$h_t - h_{A,1.1} - M y_{A,1} \geq -M$
$h_{A,1.1} - h_s - M y_{A,1} \geq -M$
$h_{A,2.out} - h_{A,2.17} - M y_{A,2} \geq -M + 60$
$h_t - h_{A,2.17} - M y_{A,2} \geq -M - 262$
$h_{A,2.17} - h_{A,2.15} - M y_{A,2} \geq -M + 108$
$h_{A,2.15} - h_{A,2.17} - M y_{A,2} \geq -M - 133$
$h_{A,2.15} - h_{A,2.11} - M y_{A,2} \geq -M + 45$
$h_{A,2.11} - h_{A,2.15} - M y_{A,2} \geq -M - 66$
\[ h_{A.2.11} - h_{A.2.5} - M \ y_{A.2} \geq -M + 51 \]
\[ h_{A.2.5} - h_{A.2.11} - M \ y_{A.2} \geq -M - 66 \]
\[ h_{A.2.1} - h_{A.2.5} - M \ y_{A.2} \geq -M - 240 \]
\[ h_{A.2.5} - h_{A.2.1} - M \ y_{A.2} \geq -M \]
\[ h_t - h_{A.2.1} - M \ y_{A.2} \geq -M \]
\[ h_{A.2.1} - h_s - M \ y_{A.2} \geq -M \]

**Fixed arcs for aircraft B:**
\[ h_{B.1.\text{out}} - h_{B.1.17} - M \ y_{B.1} \geq -M + 60 \]
\[ h_t - h_{B.1.17} - M \ y_{B.1} \geq -M - 320 \]
\[ h_{B.1.17} - h_{B.1.15} - M \ y_{B.1} \geq -M + 138 \]
\[ h_{B.1.15} - h_{B.1.17} - M \ y_{B.1} \geq -M - 191 \]
\[ h_{B.1.14} - h_{B.1.15} - M \ y_{B.1} \geq -M + 38 \]
\[ h_{B.1.14} - h_{B.1.12} - M \ y_{B.1} \geq -M - 63 \]
\[ h_{B.1.12} - h_{B.1.14} - M \ y_{B.1} \geq -M + 55 \]
\[ h_{B.1.14} - h_{B.1.12} - M \ y_{B.1} \geq -M - 63 \]
\[ h_{B.1.12} - h_{B.1.18} - M \ y_{B.1} \geq -M + 21 \]
\[ h_{B.1.18} - h_{B.1.12} - M \ y_{B.1} \geq -M - 65 \]
\[ h_{B.1.13} - h_{B.1.18} - M \ y_{B.1} \geq -M - 240 \]
\[ h_{B.1.8} - h_{B.1.13} - M \ y_{B.1} \geq -M \]
\[ h_t - h_{B.1.3} - M \ y_{B.1} \geq -M - 39 \]
\[ h_{B.1.3} - h_s - M \ y_{B.1} \geq -M + 39 \]

**Fixed arcs for aircraft C:**
\[ h_{C.1.\text{out}} - h_{C.1.16} - M \ y_{C.1} \geq -M + 60 \]
\[ h_t - h_{C.1.16} - M \ y_{C.1} \geq -M - 300 \]
\[ h_{C.1.16} - h_s - M \ y_{C.1} \geq -M + 300 \]

**Alternative arcs for the holding circle resource of aircraft A:**
\[ h_{A.1.4} - h_{A.1.1} - M \ x_{A.1.1,A.1.4} - A.1.1 - M \ y_{A.1} \geq -2M + 240 \]
\[ h_{A.1.1} - h_{A.1.4} + M \ x_{A.1.1,A.1.4} - A.1.1 - M \ y_{A.1} \geq -M - 180 \]
\[ h_{A.1.4} - h_{A.1.1} - M \ x_{A.1.4,A.1.1} - A.1.4 - M \ y_{A.1} \geq -2M + 180 \]
\[ h_{A.1.1} - h_{A.1.4} + M \ x_{A.1.4,A.1.1} - A.1.4 - M \ y_{A.1} \geq -M \]
\[ h_{A.2.5} - h_{A.2.1} - M \ x_{A.2.1,A.2.5} - A.2.5 - M \ y_{A.2} \geq -2M + 240 \]
\[ h_{A.2.1} - h_{A.2.5} + M \ x_{A.2.1,A.2.5} - A.2.5 - M \ y_{A.2} \geq -M - 180 \]
\[ h_{A.2.5} - h_{A.2.1} - M \ x_{A.2.5,A.2.1} - A.2.5 - M \ y_{A.2} \geq -2M + 180 \]
\[ h_{A.2.1} - h_{A.2.5} + M \ x_{A.2.5,A.2.1} - A.2.5 - M \ y_{A.2} \geq -M \]

**Alternative arcs for the holding circle resource of aircraft B:**
\[ h_{B.1.15} - h_{B.1.3} - M \ x_{B.1.3,B.1.8} - B.1.3 - M \ y_{B.1} \geq -2M + 240 \]
\[ h_{B.1.3} - h_{B.1.8} + M \ x_{B.1.3,B.1.8} - B.1.8 - M \ y_{B.1} \geq -M - 180 \]
\[ h_{B.1.8} - h_{B.1.3} - M \ x_{B.1.8,B.1.3} - B.1.8 - M \ y_{B.1} \geq -2M + 180 \]
\[ h_{B.1.3} - h_{B.1.8} + M \ x_{B.1.8,B.1.3} - B.1.8 - M \ y_{B.1} \geq -M \]

**Alternative arcs for the air segment resources:**
\[ h_{B.1.15} - h_{A.1.15} - M \ x_{A.1.15,B.1.15} - B.1.17 - A.1.16 - M \ y_{A.1} - M \ y_{B.1} \geq -3M + 42 \]
\[ h_{A.1.16} - h_{B.1.17} + M \ x_{A.1.15,B.1.15} - B.1.17 - A.1.16 - M \ y_{A.1} - M \ y_{B.1} \geq -2M + 42 \]
\[ h_{A.1.15} - h_{B.1.15} - M \ x_{B.1.15,B.1.15} - A.1.16 - B.1.17 - M \ y_{B.1} - M \ y_{A.1} \geq -3M + 42 \]
\[ h_{B.1.17} - h_{A.1.16} + M \ x_{B.1.15,A.1.15} - A.1.16 - B.1.17 - M \ y_{B.1} - M \ y_{A.1} \geq -2M + 42 \]
\[ h_{B.1.15} - h_{A.2.15} - M \ x_{A.2.15,B.1.15} - B.1.17 - A.2.17 - M \ y_{A.2} - M \ y_{B.1} \geq -3M + 42 \]
\[ h_{A.2.17} - h_{B.1.17} + M \ x_{A.2.15,B.1.15} - B.1.17 - A.2.17 - M \ y_{A.2} - M \ y_{B.1} \geq -2M + 42 \]
\[ h_{A.2.15} - h_{B.1.15} - M \ x_{B.1.15,A.2.15} - A.2.17 - B.1.17 - M \ y_{B.1} - M \ y_{A.2} \geq -3M + 42 \]
Alternative arcs for the runway resources:

\[ h_{B.1.17} - h_{A.2.17} + M \alpha_{B.1.15,A.2.15,B.1.17} - M y_{B,1} - M y_{A,2} \geq -2M + 42 \]

Constraints on the route selection:

\[ \begin{align*}
  y_{C.1} &= 1 \\
  y_{B.1} &= 1 \\
  y_{A,1} + y_{A,2} &= 1
\end{align*} \]

**Bounds**

\[ \begin{align*}
  h_{k,r,p} &\geq 0 \\
  h_{t} &\geq 0
\end{align*} \]

**Binary**

\[ x, y \]