DMAN-SMAN-AMAN Optimisation at Milano Linate Airport

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***Abstract*—This paper presents the design and validation of an optimization algorithm having the purpose of implementing an integrated Departure Manager - Surface Manager - Arrival Manager at Milano Linate airport. The work, based on Single European Sky ATM Research (SESAR) Solutions, has been tested on two actual case-study days, considering the airport stakeholders' objectives and constraints, and taking operative information from the Airport Collaborative Decision Making platform. Obtained results show that the proposed algorithm could increase average timeliness, reduce taxi time and fuel consumption of aircraft operating at Linate, thus contributing to reach a more sustainable and efficient air transport.**

***Index Terms*—Air Traffic Management, SESAR, DMAN, SMAN, AMAN, A-CDM, Operational Research.**

I. Introduction

Air transport generates, on a daily basis, thousands of flights that are managed in an safe and efficient way. According to forecasts, however, in the EU there will be 14% more flights in 2023 and 40% more in 2035 with respect to nowadays values ([1], [2]). Since with the currently available infrastructures and services it will be impossible to organise and manage such an increased number of flights, suitable and effective corrective measures must be envisaged and implemented from now. It is worth to be emphasised that objectives for such measures must include an enhancement not only in air traffic capacity and safety, but also in its environmental and economical sustainability.

The presented work fits in such context, and tackles Air Traffic Management (ATM) improvement by defining an optimization algorithm for computing the best solution to the problem of integrated departures, surface and arrivals management. In order to maintain the strongest links with the real world, the work has been developed using as a reference Milano Linate airport, located in northern Italy, and has been tested with actual data coming from Linate's Airport Collaborative Decision Making (ACDM).

II. Problem description

ATM has the objective to ensure safe and efficient movement of aircraft along all phases of operations, both on ground and airborne [3]. Considering the airport area, many stakeholders that operate around aircraft can be identified, each taking care of its specific tasks: Airport Operator, Ground Handlers, Air Traffic Controller Operators (ATCOs), Aircraft Operators, etc. Every single decision taken by any of the stakeholders has inevitably consequences on the other stakeholders' decisions, hence affecting the global efficiency of the whole air transport process. Therefore, from ACDM logic point of view, every single decision should not be taken for optimizing the particular task, but rather for maximising the global efficiency of the airport system.

Fostered by ENAC (Ente Nazionale per l'Aviazione Civile) and ENAV (Ente Nazionale per l'Assistenza al Volo), many efforts have been undertaken in Italy to reach the objectives set at EU level, especially for the main airports, starting from Roma Fiumicino and Milano Malpensa. Some of these efforts have been directed to the study and development of an Extendend - Arrival MANager (E-AMAN), leaving aside its integration with Departure MANager (DMAN), Surface MANager (SMAN) and ACDM [4]. These, however, are essential enabling tools to reach important objectives (such as the reduction of both queues at the runway threshold and of quantity of fuel burned during taxi time), and for the exploitation of the maximum airport traffic potential.

This paper briefly presents the work developed in [5], where it has been decided to approach and solve the aforementioned problem with a vision of departures and arrivals management integrated with the ground handling, in close connection with ACDM. The work has been contextualised at Linate, Milan city airport, which, in 2016 Italy's ranking, is [6]:

- *3rd* for aircraft movements (118,535);
- *4th* for passenger movements (9.7 Mi);
- *8th* for cargo movements (15 ktons).

Among the other reasons, a full ACDM platform has been active for several years at Linate.

Linate (figure 1) has one main Runway (RWY) which is normally used for departures and arrivals (RWY 36-18), and a second one, parallel, that can be (but rarely is) used for general aviation (RWY 35-17). Parallel to the main runway, the main taxiway runs from the north apron to RWY 36 holding point. Save for particular circumstances, RWY 36 is normally in use. In order to reach the holding point of RWY 36, general and business aviation aircraft, parked at the west apron, must travel along the taxiway running north of the main runway, and then go through the main taxiway, which is also used by commercial flights. Hence, the single main taxiway can constitute a bottleneck that introduces ground traffic congestions and delays that can be avoided by means of a properly designed optimization algorithm for defining the optimal aircraft ground sequence. In addition, the necessity to use the single runway in mixed mode (concurrently for both departures and arrivals) constitutes a challenge for an algorithm that has the objective to define the overall optimal flights schedule.

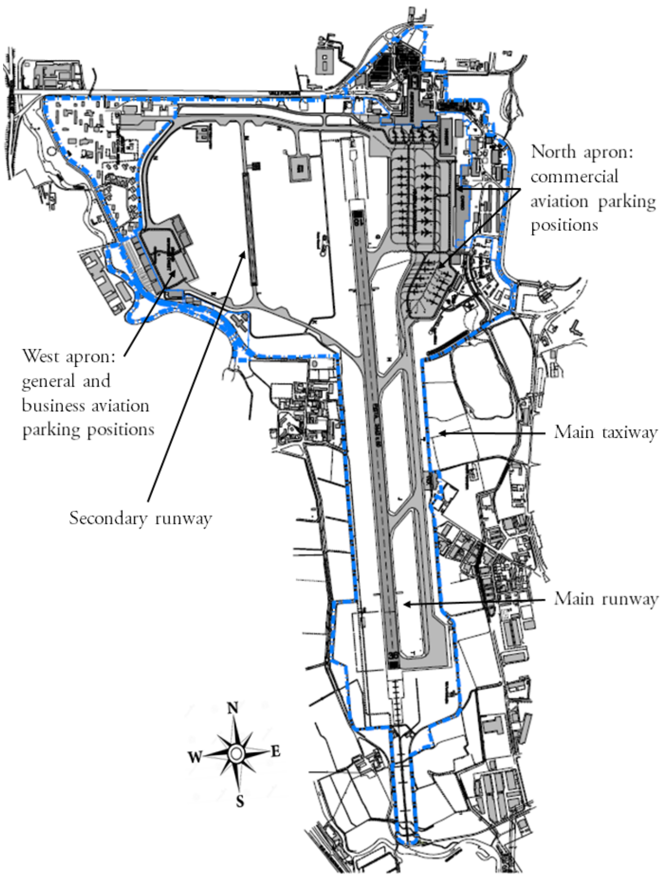

Figure 1: Map of Linate airport. [https://goo.gl/G8uqYN] (See ADPML2-1 [7] for a detailed and up-to-date map.)

III. Proposed solution approach

As previously mentioned, to yield the best results on the overall efficiency of the airport system, any stakeholder decision should be thought of as *global* rather than *local*. However, because of the high complexity of the problem, manually finding global solutions is simply not viable. A properly defined optimization algorithm can therefore represent a valuable support to help operators take decisions and exercise control on the overall process. Following EU guidelines ([8], [1] with SESAR Essential Operational Changes and [9]), such algorithm should consider Arrival MANager (AMAN), DMAN, SMAN and ACDM concurrently to obtain a global solution and provide ATCOs with the optimal Target Start up Approval Time (TSAT) and Target Take-Off Time (TTOT) for departures, and Target LanDing Time (TLDT) for arrivals.

In order to obtain a solution for the integrated DMAN-SMAN-AMAN problem, the presented study followed the works of Kjenstad et al. ([10], [11]), which were applied to German Hamburg airport (where there are two runways) and Swedish Arlanda airport (where there are three runways), and have been considered as the *baseline formulation*. Their approach consisted in an heuristic decomposition of the integrated problem in three sub-problems (ground routing problem, runway scheduling problem and ground scheduling problem), all modelled as Mixed Integer Linear Programming (MILP). Although this approach may not give the optimal solution, it allows to dramatically reduce the computational effort, giving the solution almost in real time. It is therefore suitable for dynamically following the unavoidable and unpredictable changes present in real-world scenarios (e.g. traffic or meteorological variations, closing of a runway, etc.), providing ATCOs (and potentially other stakeholders) with up-to-date information and cues.

Some modifications and additions have been applied to the cited baseline formulation, in order to improve it on one hand and to better fit it to the context of Linate on the other.

Ground routing problem. This is the first step considered by the algorithm (SMAN). The aim is to compute, for each aircraft, a feasible route from its parking stand to the RWY and vice-versa, minimizing taxi time and exploiting all airport resources. Developed Linate airport topology is represented in figure 2 with an oriented line graph. Green colour is assigned to parking positions, while double arrow arcs symbolise parking stands with push-back. The runway is depicted in blue, while red nodes represent holding points: as in the real airport, they are useful to the algorithm to let aircraft wait and avoid conflicts, and for this reason they are used in step 3 to obtain an optimal (feasible) solution to the ground schedule problem. Nodes indicated as Q_i represent release points for push-backs. Defining u_f^a a binary variable which considers if an arc a of the airport graph is assigned or not to flight f, and l_f^a the running time for f through a, the objective function can be written as:

$$\min \sum_{f\in F}\sum_{a\in A} u_f^a \cdot \left(l_f^a + \tfrac{0.1}{card(F)} \sum_{f\in F} u_f^a \right). \qquad (1)$$

Ground routing problem is a shortest path problem, and has been modelled as a modified maximum flow model, in which the units to send from the source to the sink are flights F that have to be routed. The running time l_f^a, which represents a cost associated to each arc, has been extracted from ACDM platform.

It can be noted that the second term within parenthesis increases the time cost l_f^a of arc a proportionally to the usage of that arc by all considered flights, and is pre-multiplied by the term $\frac{0.1}{card(F)}$ in order to assign a lower weight to resources utilization with respect to the choice of the shortest path. This term was not present in Kjenstad et Al.'s works, and has been conceived to allow the algorithm to utilise every single resource of the airport and optimise the traffic flow; without this, in fact, a traffic congestion could happen if too many aircraft are assigned the same path (although, as it will be shown, step 3 tries to cancel traffic delays). Additionally, if the cost-time of one particular arc is lower, even only slightly lower than that of another, the algorithm would always assign the former in the calculated shortest path for aircraft, reducing, in practice, the exploitation of the full airport capacity (this can be the case, for example, of multiple instances of almost time-equal taxiways running towards/from parallel runways or de-icing zones, or in general in the airport layout). The downside of this approach is that the model becomes non linear (Non Linear Programming (NLP)) in the variable describing the usage of arcs of the graph u_f^a, so the problem is NP-Hard, but it has been verified that the impact of this consequence on computational time is minimum.

The constraints that have been considered regard entry point (parking position for departures and runway for arrivals), exit point (runway for departures and parking position for arrivals), balance from an arc to another, the fact that cycles are prohibited, and the impossibility to run a specific taxiway if that particular taxiway is unusable for the considered aircraft (i.e. a liner can't pass through the west apron). Arrival and departure gates are assumed assigned (by the Airport Operator in ACDM), and cannot be changed.

Runway scheduling problem. This is step 2 of the integrated problem decomposition, whose goal is to find an optimal scheduling for arrivals and departures at the RWY (DMAN+AMAN). Desired take-off and landing times are defined. Because of Eurocontrol-related necessities, Calculated Take-Off Time (CTOT) can be assigned to a departing flight, therefore it *must* depart at that particular time. If CTOT is not assigned, then Expected Take-Off Time (ETOT), computed as Estimated Off-Block Time (EOBT) + Estimated taXi-Out Time (EXOT) is used as desired take-off. Differently from the baseline formulation, flights with assigned CTOT must always take-off within their Slot Tolerance Window (STW), while others could be *dropped* by the algorithm. In this case a new ETOT and, consequently, a new Departure Tolerance Window (DTW), will be assigned to that flight. The same strategy is applied to arriving aircraft, for which the desired landing time is Estimated Landing Time (ELDT), around which Arrival Tolerance Window (ATW) is defined. Hereafter it will be indicated with δ_d the time at which a particular departure d is expected to take-off, i.e. either ETOT or CTOT, and with λ_l the ELDT associated with a particular arrival l.

CTOT, ETOT and ELDT have been extracted from ACDM, while tolerance windows for departing aircraft STW and DTW have been defined as per Eurocontrol [3]. ATW, instead, has been determined taking in consideration the amount of time every aircraft spends to move from the holding point to the runway, and the fact that the approach phase is quite critical, so its time variation should be limited by ATCOs. Tolerance windows are then defined as:

- DTW: by default 15 min. before and 15 min. after ETOT;
- STW: by default 5 min. before and 10 min. after CTOT;
- ATW: fixed at 15 min. before and 5 min. after ELDT.

Following Kjenstad et Al.'s formulation, let α_d and α_l be the lowest times associated with the tolerance window of a departing flight (H_d, which can either be DTW or STW) or of an arriving flight (H_l, equal to ATW), and β_d and β_l the highest values. So $H_d = \{\alpha_d \ldots \beta_d\}$ and $\delta_d \in H_d$, $H_l = \{\alpha_l \ldots \beta_l\}$ and $\lambda_l \in H_l$. Finally, the time horizon H is the time window between the lowest α and the highest β among all the flights that the algorithm has to schedule, for which $H_d \subseteq H$ and $H_l \subseteq H$ (figure 3).

For each departure (arrival) $f \in F$ and each time period $t \in H_f$, a binary variable x_{ft} is introduced which is 1 if and only if f takes-off (lands) at time t. Taking-off or landing at time t has a cost c_{ft}. For departure d (arrival l) such cost increases with $|t-\delta_d|$ ($|t-\lambda_l|$). For each departure d without a CTOT, a binary variable y_d is introduced which is equal to 1 if and only if d is dropped. Dropping a departure $d \in D$ has large cost w_d (fixed, for computational reasons, to the speculative value of 100).

Basically, the algorithm attempts to assign, within each specific tolerance window H_f, a departure time or an arrival time ($x_{ft} = 1$): the former is the optimal TTOT and the latter is the optimal TLDT for the integrated problem DMAN+AMAN. As an addition to the baseline formulation, in the presented approach if take-off time cannot be assigned to a particular departure ($y_d = 1$), that flight will be iteratively postponed until time fits the global schedule.

The objective function can be formulated as the minimization of the cost of dropped flights plus overall deviation from the desired arrival and departure times:

$$\min \sum_{d \in D} w_d \cdot y_d + \sum_{f \in F, t \in H_f} c_{ft} \cdot x_{ft} \tag{2}$$

Some constraints have been introduced in the model for the purpose of taking into consideration operative procedures, like the assumption that an arriving aircraft will always land (i.e. go-around and/or emergency procedures are not considered), that a departing aircraft with CTOT assigned must take-off while others can be dropped (at high cost), and that an aircraft cannot take-off before it has reached the runway-i.e. not earlier than Target Off-Block Time (TOBT) + EXOT. Moreover, time separation between arrivals and departures has been modelled, in order to consider wake vortex turbulences and standard arrival/departure procedures.

Since the model has a linear objective function and constraints, but integer variables, it belongs to the class of Integer Linear Programming (ILP) problems.

Ground scheduling problem. As in Kjenstad et Al.'s work, this is step 3 of the integrated problem decomposition, whose goal is to establish the time t (continuous variable) at which a flight $f \in F$ should enter every node and arc of its route

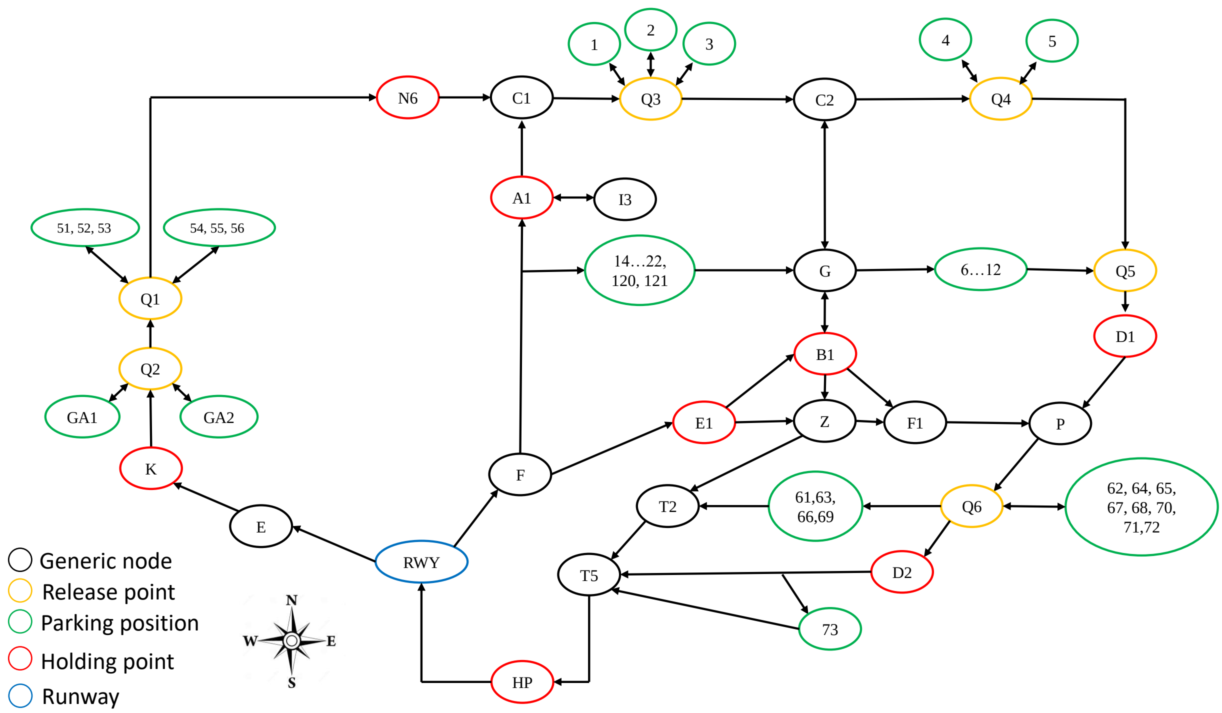

Figure 2: Graph of Linate airport.

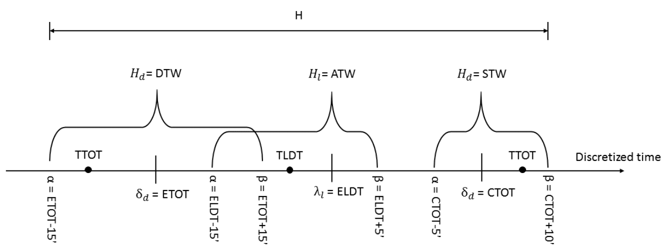

Figure 3: Times and tolerance windows for the runway scheduling problem.

$r_f = (v_0, a_1, v_1, a_2, \ldots, a_k, v_k)$, for obtaining a completely conflict-free schedule, and for guaranteeing smooth traffic flow through taxiways. It is necessary to associate a schedule vector $t_f = (t_f^{v_0}, t_f^{a_1}, t_f^{v_1}, t_f^{a_2}, \ldots, t_f^{a_k}, t_f^{v_k})$ with the route of each flight (SMAN). The overall schedule t must:

- assign a schedule time (input time) to arcs and nodes of shortest paths computed at step 1;
- satisfy the order of arrivals and departures on the runway established at step 2;
- obey to all precedence and separation constraints;
- minimise overall taxi time, that is the time that aircraft spend between the parking position and the runway with engines on, and vice-versa.

With $t_l^{g_{in}(l)}$ the time an arrival aircraft is scheduled to arrive to its gate is denoted, while $t_d^{g_{out}(d)}$ indicates the entry time in the arc following the node representing the gate, that is the time a departing aircraft leaves its gate. These times, from the algorithm perspective, correspond to Target In-Block Time (TIBT)-the former-and to TSAT-the latter. Entry and exit points at the RWY, computed at step 2, are indicated with t_l^{RWY} (TLDT) and t_d^{RWY} (TTOT). The objective function can thence be formulated as:

$$\min \sum_{l \in L} \left(t_l^{g_{in}(l)} - t_l^{RWY} \right) + \sum_{d \in D} \left(t_d^{RWY} - t_d^{g_{out}(d)} \right) \quad (3)$$

Ground scheduling problem can be seen as a job-shop scheduling problem, in which aircraft represent jobs to be processed by machines (airport resources like nodes and arcs of the airport graph).

The schedule must then satisfy *simple* constraints, such as the observance of the optimal runway schedule found at step 2, the compliance with the route sequence found at step 1, the fact that an aircraft cannot stop on arcs (but only at parking positions and holding points) and cannot leave its stand before the last updated TOBT derived from ACDM platform. Moreover, *disjunctive* pairs of constraints must be modelled (using binary variables), because two aircraft cannot occupy the same node at the same time and must be separated in time either for safety reasons or for operative procedures (like at parking positions or release points). Holding points, where aircraft can queue for holding, constitute an exception to the latter constraint.

Since the model has a linear objective function and constraints, but both integer and continuous variables, it belongs to MILP problems.

Integrated vision of the algorithm . The presented algorithm has been applied to two case-study days for which ACDM data has been made available to authors. This means that since the algorithm has been run off-line, the progress of time has been simulated with a fictitious parameter. With this parameter, it has been possible to implement some new logic blocks with respect to the baseline formulation, and local procedures (airport regulations, ATCO procedures, etc.) have also been applied.

The algorithm flowchart is presented in figure 4, where the new logic blocks are highlighted with red hexagons:

- if at step 2 take-off time can't be assigned to a departure (with no CTOT), the flight is *dropped* and its ETOT is postponed until an optimal TTOT is found (as it has been pointed out above);
- if a departure is scheduled within 15 minutes from current time, that flight is *scheduled* so its TSAT, TTOT and path cannot be modified any more, in order to give ATCO the final optimal values;
- similarly, if an arrival is scheduled within 15 minutes from current time, that flight is *on final* so its TLDT, TIBT and path cannot be modified, in order to give ATCO the final optimal values.

From the flowchart it can be understood that, at each iteration, the algorithm has to concurrently schedule new and old flights, taking into consideration the fixed optimal times and paths already computed for *scheduled* and *on final* flights (which are not yet *take-off* or *on-blocks*), and re-optimising aircraft that do not have fixed times or paths (among which *dropped* flights are).

IV. Results

Presented NLP, ILP and MILP problems have been implemented in AMPL modelling language [12], and solved by CPLEX solver version 12.6.3.0 on a PC with Intel i7 CPU, 4 cores (running at 1.6 GHz) and 4 GB RAM. The algorithm has been applied to all flights of the two case-study days: November, 8^{th} 2016 and February 15^{nd} 2017 (two days without particular traffic congestion problems). The average run-time for the scheduling simulation of all flights (almost 300 per day) was 25 seconds, with less than 0.1 seconds for solving each step, confirming that heuristic decomposition is effectively useful for obtaining very low computational time. Results have then been compared with what actually happened on those days.

As a means to better describe the presented algorithm's *modus operandi*, let us introduce two definitions:

- *target* values: optimal values computed by the algorithm (TTOT, TSAT, TLDT and TIBT), and values estimated by ACDM platform, which are not derived from an optimization routine (TSAT, TTOT).
- *actual* values: actual times at which flights operate on the airport following a First Come First Served (FCFS) procedure, which are recorded in ACDM platform (Actual Off-Block Time (AOBT), Actual Take-Off Time (ATOT), Actual Start up Approval Time (ASAT), Actual In-Block Time (AIBT), Actual LanDing Time (ALDT)).

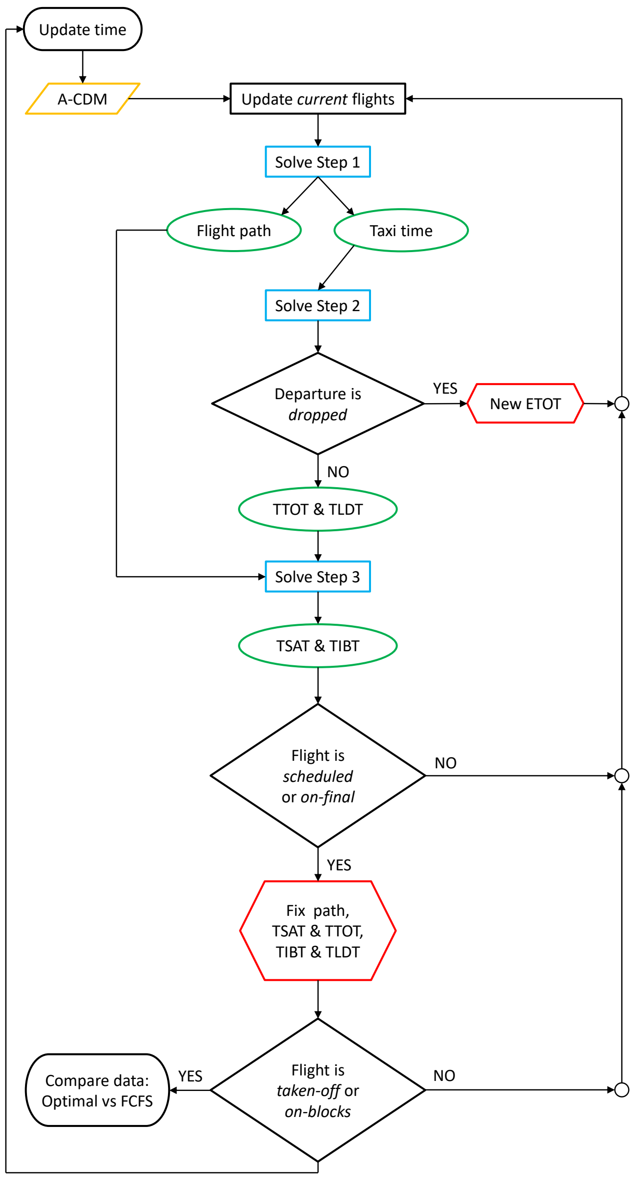

Figure 4: Algorithm flowchart.

For the comparison between FCFS and optimal procedures three different problems arose:

- it was not possible to directly compare *target* values, because they were not available for arriving aircraft since AMAN is not implemented at Linate so far;
- it was not possible to directly compare *actual* values, because the algorithm was to be run off-line, so optimal ones do not exist;
- it was not possible to compare *actual* values with optimal *target* values, because this would have delivered too optimistic results.

For these reasons, it has been decided to compute an estimation of actual values also for the optimal case, and compare real FCFS values with these *fictitious* optimal ones. This has been done deriving from ACDM delay information for flights following FCFS procedure, and considering that part of such delay was due to airport operations, especially at parking positions (differences between actual and authorization start up and push back times, handling procedures, and others implemented by the airport stakeholders). This delay, then, has been added to optimal target values in order to simulate real operations following the optimization algorithm.

In order to define a set of parameters suitable to evaluate the quality of results, a preliminary consideration has been done. It is quite common, in fact, to use *delay*, defined as the difference between the actual time of occurrence of a particular event and its target time, as a judging parameter. The evaluation logic for delay is obviously *the less, the better*, but given that it's a signed quantity, since actual time of occurrence can anticipate target time, this logic leads to the consequence that negative values are highly desirable. However, for a number of events considered in the present study, both delay and advance have a negative impact on optimal ATM. It has therefore been introduced, and will be used to evaluate some of the results, a different quantity, defined as the absolute value of delay: *time deviation*.

To judge the quality of results, three parameters have been considered: average time deviation at the runway, mean taxi time and mean fuel consumption. These are useful to understand whether the proposed algorithm is able to meet SESAR objectives, like time deviation at runway threshold, reduction of fuel consumption, increase of traffic fluidity, enhancement of safety along taxiways and stakeholders consciousness. Other values, like time deviation at parking position (which is commonly used for estimating airports performances and quality levels), would not have given the same match grade with European objectives. Moreover, the proposed algorithm acts on departing time of aircraft from parking positions in order to have less traffic on taxiways and to have less delay during the overall flight, so aircraft could, in theory, wait some additional minutes at parking in order to optimise global efficiency.

Time deviation at the runway has been computed from the absolute value of the mean difference between actual and *desired* values[1], taxi time from the mean difference between actual off-block (in-block) and take-off (landing) times, and fuel consumption starting from the mean difference between actual start up (shut down) and take-off (landing) times. The computation of fuel consumption followed ICAO directives [13], which state that the fuel used throughout taxi run can be estimated, to a first approximation, taking the fuel flow data from the Engine Emissions Data Bank, and knowing the number of the aeroplane's engines.

[1]For departures, operative delays at the runway are already computed by the algorithm, so actual optimal times are considered equal to computed target times. This way, desired values for the optimal case are CTOT and ETOT, while for FCFS procedure TTOT computed by ACDM has been utilised. Similarly for arrivals, for which the desired time is ELDT, both for optimal and FCFS procedures.

Results obtained from the analysis of November 11$^{\text{th}}$ are reported in tables I, II and III, where it can be seen that the algorithm can optimise the flights scheduling, with the exception of time deviation at the runway, in which the algorithm obtained the same results of the controllers following FCFS procedure. This derives from the fact that November 11$^{\text{th}}$ day was not a critical day in terms of traffic congestion, and shows that the algorithm performance isn't worse than ATCOs'.

	LDTD	Taxi time	Fuel usage
Optimal	1.19 min (1.20)	4.13 min (2.11)	7.8 ton
FCFS	1.61 min (1.37)	4.30 min (0.94)	8.1 ton
Opt vs. FCFS	−26%	−4%	−4%

Table I: Arrivals results of 8/11/2016.

	TOTD	Taxi time	Fuel usage
Optimal	2.38 min (3.73)	10.18 min (3.91)	22.1 ton
FCFS	2.38 min (2.89)	11.31 min (4.43)	23.7 ton
Opt vs. FCFS	..	−10%	−7%

Table II: Departures results of 8/11/2016.

	Time Deviation	Taxi time	Fuel usage
Optimal	3.55 min	14.31 min	29.9 ton
FCFS	3.99 min	15.61 min	31.9 ton
Opt vs. FCFS	−11%	−8%	−6%

Table III: All flights results of 8/11/2016.

Results obtained from the analysis for February 15$^{\text{th}}$ are reported in tables IV, V and VI, where where better results can be noted with respect to both FCFS and case-study day #1.

In all tables, values of the standard deviation of Take-Off Time Deviation (TOTD), LanDing Time Deviation (LDTD) and taxi time are presented in brackets. It can be noted that for arrivals LDTD standard deviation is lower for the optimum solution than for FCFS, while for departures TOTD it is greater: this derives from the fact that at Linate arrival times are at present not taken into particular consideration, while departing flights are already managed following some kind of optimization process. Moreover, dropped flights could compromise this value, so some limitations on re-iterations should be considered with airport stakeholders for the purpose to obtain both timeliness and low deviation from the mean value. On the contrary, the optimal standard deviation of taxi time for departing aircraft, which at Linate is by far more important than for arrivals, is greater for optimal than for FCFS, meaning that having a general view of the optimization process works better than merely concentrating on time deviation values.

TOTD is presented in figure 5, in which it can be noted that the algorithm is well capable to accomplish the desired time of departure. Particular attention should be given to the zero time deviation columns: compared to FCFS performance, with the optimal solution 159 vs. 96 flights (63 more, $+65\%$) depart at their desired time, meaning that they are neither late nor in advance, and this is a good result for the general management of airport resources. Similar considerations can be drawn for landing aircraft, whose results are represented in figure 6 in terms of LDTD.

	LDTD	Taxi time	Fuel usage
Optimal	1.08 min (1.38)	3.65 min (5.29)	5.7 ton
FCFS	1.71 min (5.03)	4.01 min (0.30)	7.5 ton
Opt vs. FCFS	−37%	−9%	−23%

Table IV: Arrivals results of 15/2/2017.

	TOTD	Taxi time	Fuel usage
Optimal	2.36 min (3.15)	9.59 min (3.88)	20.6 ton
FCFS	2.72 min (2.54)	11.70 min (4.39)	24.5 ton
Opt vs. FCFS	−13%	−18%	−16%

Table V: Departures results of 15/2/2017.

	Time Deviation	Taxi time	Fuel usage
Optimal	3.44 min	13.24 min	26.3 ton
FCFS	4.43 min	15.71 min	31.9 ton
Opt vs. FCFS	−23%	−16%	−18%

Table VI: All flights results of 15/2/2017.

Outbound Taxi Time Difference (OTTD), defined as the difference between optimal and FCFS taxi time, is presented in figure 7. It can be noted that most aircraft have negative values, meaning that the optimal scheduling is capable to save taxi time with respect to FCFS. Note that in this figure inbound taxi time is not considered, since at Linate this is not of particular interest because parking positions are very close to the runway exit points.

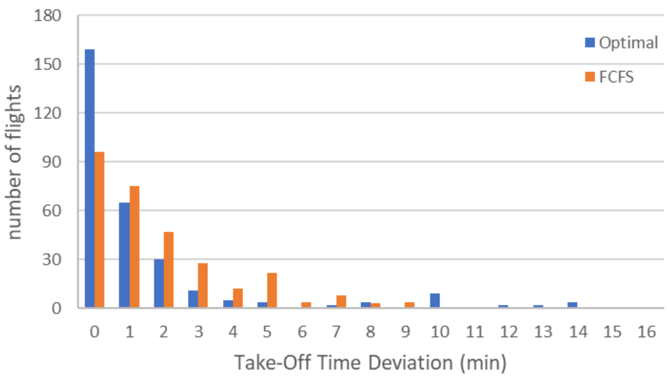

Figure 5: TOTD for both case-study days.

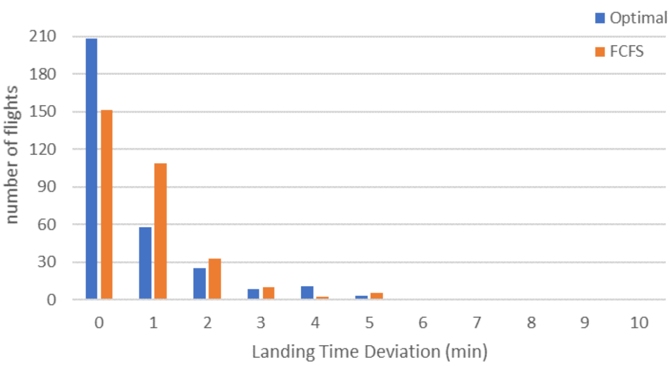

Figure 6: LDTD for both case-study days.

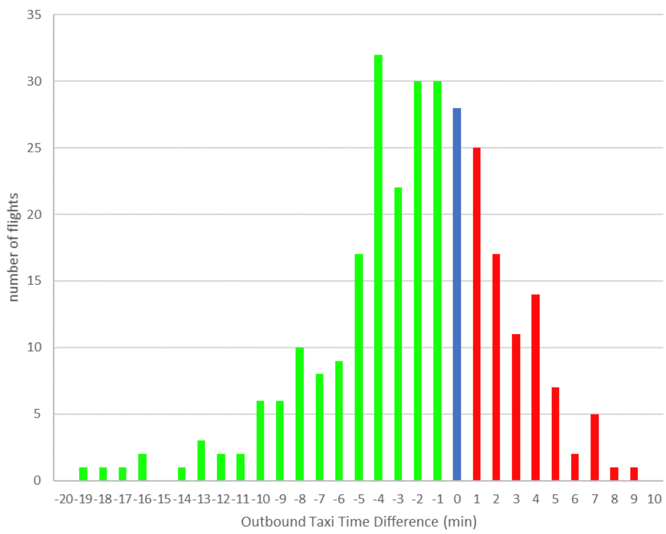

Figure 7: OTTD for both case-study days.

In general, if controllers had been able to follow the optimal scheduling, they would have saved a few-but valuable-minutes in terms of time deviation at the runway and taxi time. This corresponds to have less airport noise, to increase safety (since there would have been less aeroplanes simultaneously running on taxiways), and also to save a considerable amount of fuel during the taxi. Therefore, as a last analysis CO_2 potentially saved by the algorithm has been calculated. Following ICAO directives [13], with a conversion ratio of $3.16\ \mathrm{kg}_{CO_2}/\mathrm{kg}_{\mathrm{fuel}}$ it can be computed that, on the first day 6.9 ton of CO_2 would not have been emitted, while on the second day the saving would have been 17.8 ton, respectively almost equivalent to an average 20 kg and 56 kg of CO_2 saved by each aircraft in the two days. In addition, taking the mean value of the price of Jet A-1 fuel for November 2016 and February 2017 [14], monetary saving potentially available for airlines thanks to the algorithm effectiveness could be evaluated: Alitalia, the major airline company operating at Linate, would have saved an average of about $1,900$ Euro each day.

V. Conclusions and Future Works

ATM improvement is a fundamental objective for the EU, and through SESAR programme important results have been achieved. Looking at the Essential Operational Changes defined within the European ATM Master Plan, the work presented in this paper tried to understand if ATM could be improved at Linate airport. The objective was to design an algorithm capable to help airport stakeholders, in particular ATCOs, to take decisions on aircraft start up time, take-off time and landing time, optimizing the global efficiency of the airport system. By exploiting specific tools of Operational Research, the DMAN-SMAN-AMAN integrated problem has been heuristically decomposed in three sub-problems and adapted to the local context. The comparison between algorithm results and what actually happened on two case-study days shows potential benefits in reduction of average values of flight untimeliness, taxi time and fuel consumption, yielding s lower noise impact, an increased safety, and a considerable save on CO_2 emissions and money every day.

The presented algorithm permits to obtain the described good results with very low computational time, substantially improving ATM at Linate airport. Additional analyses should be conducted taking into consideration different operative conditions, possibly running the algorithm in real-time, in order to compare the *actual* optimal values with the *target* ones.

Future developments may include dynamic computation of delay along taxiways, in order to achieve a complete Variable Taxi Time (VTT) calculation and a full implementation of SMAN. In this work, in fact, running times on taxiways have been taken from airport ACDM data, in which they are considered fixed-and therefore independent from meteorological conditions. For future works, however, a computation of the actual running time in every single time of the day and day of the year-for every relevant meteorological condition-would be crucial for a further improvement of the algorithm output reliability.

Additionally, de-icing shall be modelled, but only if and when confidence on times of that particular phase will be sufficiently high: for the optimization algorithm efficiency sake, in fact, the availability of precise and up-to-date input data it is pivotal. Since de-icing procedures strongly depend on the type of ice, and type of aircraft and operator's own procedures, in this work it has not been implemented.

Moreover, procedures for taking in consideration the characteristics of the recently-introduced electric taxi capability could also be developed and integrated, since it introduces remarkable differences in taxi times, push back procedures, runaway crossing and other taxi-related details.

Finally, an implementation in a larger airport, like for example Milano Malpensa, could be interesting, because it has two main runways and a complex taxiway network, a situation that can the presented algorithm advantages, delivering, as for Linate, a *more sustainable and high-performing aviation*.

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LIST OF ACRONYMS

ACDM Airport Collaborative Decision Making
AIBT Actual In-Block Time
ALDT Actual LanDing Time
AMAN Arrival MANager
AOBT Actual Off-Block Time
ASAT Actual Start up Approval Time
ATC Air Traffic Control
ATCO Air Traffic Controller Operator
ATM Air Traffic Management
ATOT Actual Take-Off Time
ATW Arrival Tolerance Window
CTOT Calculated Take-Off Time
DMAN Departure MANager
DTW Departure Tolerance Window
E-AMAN Extendend - Arrival MANager
ELDT Estimated Landing Time
EOBT Estimated Off-Block Time
ETOT Expected Take-Off Time
EXOT Estimated taXi-Out Time
FCFS First Come First Served
ICAO International Civil Aviation Organization
ILP Integer Linear Programming
LDTD LanDing Time Deviation
MILP Mixed Integer Linear Programming
NLP Non Linear Programming
OTTD Outbound Taxi Time Difference
RWY Runway
SES Single European Sky
SESAR Single European Sky ATM Research
SMAN Surface MANager
STW Slot Tolerance Window
TIBT Target In-Block Time
TLDT Target LanDing Time
TOBT Target Off-Block Time
TOTD Take-Off Time Deviation
TSAT Target Start up Approval Time
TTOT Target Take-Off Time
TWY Taxiway
VTT Variable Taxi Time

REFERENCES

[1] EU and Eurocontrol, "European ATM Master Plan - Executive View", 2015
[2] Eurocontrol, "Eurocontrol seven-year forecast", www.eurocontrol.int/articles/forecasts, last visited on 03.03.2017.
[3] Eurocontrol, "ATM Lexicon", https://ext.eurocontrol.int/lexicon/index.php/Main_Page, last visited on 09.09.2017.
[4] Eurocontrol and ENAV, "Local Single Sky Implementation (LSSIP) ITALY", 2015.
[5] Giovanni Pavese, "An integrated solution for the optimization of the departures, surface and arrivals management at Milano Linate airport", MSc Thesis, Politecnico di Milano, 2017.
[6] Assaeroporti, http://www.assaeroporti.com/, last visited on 03.03.2017.
[7] ENAV, Aeronautical Information - AIP, https://www.enav.it/sites/public/en/Servizi/areonautical-information.html, last visited on 03.03.2017.
[8] SESAR Joint Undertaking, "SESAR solutions catalogue - Second edition", 2017, DOI:10.2829/0404
[9] SESAR, "6.8.4-S01V3 Final OSED", Edition 00.01.01, 2015.
[10] D. Kjenstad, C. Mannino, T. E. Nordlander, P. Schittekat, M. Smedsrud, " Optimizing AMAN-SMAN-DMAN at Hamburg and Arlanda airport", Third SESAR Innovation Days, *26th* - *28th* November 2013.
[11] D. Kjenstad, C. Mannino, P. Schittekat, M. Smedsrud, " Integrated Surface and Departure Management at Airports by Optimization", 2013.
[12] Robert Fourer, David M. Gay, and Brian W. Kernighan, "AMPL: A Modeling Language for Mathematical Programming", 2003.
[13] ICAO, "Airport Air Quality Manual", 2011.
[14] IATA, "Jet Fuel Price Monitor", http://www.iata.org/publications/economics/fuel-monitor/Pages/index.aspx, last visited on 29.03.2017.