TERMINAL AREA "GREEN" OPTIMIZATION USING JOB-SHOP SCHEDULING TECHNIQUES

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Keywords: *job-shop scheduling, aircraft sequencing*

Abstract

In the Approach Control Area an important match for reducing aviation environmental impact is played.
Aircraft Sequencing Problem (or Aircraft Landing Problem) has been widely studied for the last years in order to find the optimal sequence that maximizes the number of landing aircraft in the time unit.
The model we propose is based on no-wait Job-Shop Scheduling with sequence dependent machine set up time and release date.
In our model STAR and SID are divided into air segments: runways and air segments of arrival and departure procedures are modeled as machines, airplanes are considered as job with release date.
Each machine i processes an Aircraft/Job and produces a cost for the environment.
The impact of the pollution in each element of the grid map depends on the related machine.
The "green" sensitivity of each grid map element is defined by using numerical models.
Starting from existing Job-Shop Scheduling models, by means of elitary Genetic Algorithm, the number of movements in the time unit is optimized to manage the Approach airspace.
Finally, an experimental analysis is presented, it has been performed on a case study of Bologna airport terminal area.

1 Introduction

Air traffic in Europe is expected to significantly increase in the next decades. Today's traffic levels are supposed to double by 2020 while air traffic system capacity is not expected to augment proportionally.
As regards capacity the most critical areas are terminal areas around airport. Currently, air traffic flows often saturate the capacity of terminal areas. This saturation is critical for both controllers' and pilots' workload, for the costs associated to flights delays and, more generally, for air traffic system efficiency.
Therefore, airports and terminal areas are universally recognized as air traffic system bottlenecks.
Environmental impact is gaining importance in the evaluation of both existing and proposed changes to airport and airspace operations. The Clean Sky Joint Technology Initiative of the European Commission, the Single European Sky Advanced Research (SESAR) project, the FAA's Operational Evolution Plan (OEP) and the JPDO's Next Generation Air Transportation System (NGATS), specifically highlight environmental impacts as a major factor to be addressed in the evolving infrastructure, technology and operational concepts for the Air Traffic System.
Aircraft Landing Problem (ALP) has been widely studied for the last years in order to face to the complex task of scheduling arriving aircraft to the available runways.
Different approaches have been proposed that examine the segment of air traffic control, the traffic management advisor, to minimize delays and environmental impact and to satisfy safety constraints dealing with the separation to be maintained between various types of aircraft.
The aircraft sequencing has been extensively discussed. The problem was presented first by J. E. Beasley et al. [1] through a mathematical formulation of the problem as a mixed-integer zero–one program. After relaxing binary variables and strengthening the formulation with

additional constraints the problem is solved optimally with a linear programming based tree search algorithm. The formulation of the problem is presented for the single runway case and is extended to the multiple runway case.
This work was based on an earlier mixed integer linear programming formulation and a Genetic Algorithm (GA) approach by Abela et al.[2].
Cheng et al. addressed four different genetic search formulations, a broader term incorporating both GAs and Genetic Programming (GP), applied for multiple runways [3].
In [4] Ernst and Krishnamoorthy proposed an exact method based on branch and bound and a heuristic one based on GA: the model is applicable to a mix of takeoffs and landings on the same or on different runways.
In [5], V. Ciesielski and P. Scerri presented a series of experiments on landing data for Sydney Airport on the busiest day of the year to investigate the applicability of Genetic Algorithms to the problem of real time scheduling of aircraft arrival time.
H. Pinol and J.E. Beasley applied two genetic approaches to the ALP: the scatter search and bionomic algorithm for the multiple runway presenting a mathematical formulation with two types of objective functions: a linear and a nonlinear one[6].
Job-Shop scheduling techniques have been widely used to solve sequencing problems.
Meta-heuristics such as Taboo Search (TS) [7], GAs, and Simulated Annealing (SA) [8], have been applied much in recent years to solve the Job-Shop Scheduling Problem (JSSP).
G. Bencheikh et al. propose a formulation of the ALP as a JSSP: they resolve the ALP with hybrid method, called ACOGA (Ant Colony Optimization Genetic Algorithm) which combines two metaheuristics: GA and Ant Colony Optimization (ACO) [9].
The cited applications underline that genetic search methods are particularly well suited to TMA (Terminal Control Area) problems because of their robustness in domains that are discontinuous, non-convex, non-linear or non-analytic.
The method defined in this paper models the TMA as a JSSP.

Starting from these models, our goal is to manage the approach airspace optimizing the aircraft sequencing in order to maximize the capacity of arrivals and departures in the time unit, keeping down the environmental impact. The complexity and the dynamic of the problem require a heuristic approach: a genetic algorithm has been applied.

1.1 Aircraft Sequencing Problem (ASP)

Upon entering within the radar horizon of air traffic control (ATC), a plane requires ATC to assign it a landing time and a runway to land.
The landing time must lie within an earliest time and a latest time, these times being different for different airplanes.
The earliest time represents the time a plane can land if it flies at its maximum airspeed. The latest time represents the time a plane can land if it flies at its most fuel efficient airspeed while holding for the maximum allowed time. The target time of a plane is the time it would land if it is required to fly at cruise speed.
If ATC requires the plane to either slow down, hold or speed up, a cost will be incurred that grows as the difference between the assigned landing time and the target landing time.
The time between a particular plane landing and the landing of any successive plane must be greater than a specified minimum. Moreover it has to be taken into account the separation time, which depends on the planes involved and on aerodynamic considerations.
In order to reduce the complexity of the problem, some simplifications are applied:

- single runway airport;
- limited number of standard routes;
- limited number of airplanes in the sequence;
- inbound air traffic is modeled using Job-Shop Scheduling Technique, whereas the presence of outbound air traffic is considered only for the occupation of the runway;
- optimization is performed on the landing sequence.

Standard procedures are considered. Noise and pollution influence has been evaluated and inserted in the problem by means of environmental factors in order to obtain the higher capacity consistent with environmental constraints.

2 TMA modeling

The ASP is modeled as a no wait job-shop scheduling model with sequence dependent machine set-up times and job release dates.
Terminal area model is described by three main elements:

- Airplanes
- Airspace
- Environment

Each element is modeled in a proper way in order to be implemented in a job-shop scheduling model, see L.Bianco et al.[10].
We define the entrance time (ET) of an arriving aircraft as the time when it enters the TMA at a given entry fix and is ready to start the approach procedure for landing. Following [10], the arrival flow control problem can be stated as follows. Given a set of aircrafts and their ETs for all the fixes in a given time interval (typically one or two hours), the runway occupancy times, the geometry of the approach paths and corresponding aircraft speeds, the cost associated to each path leg depending on the a/c type and area sensitivity, assign to each landing a/c a starting time for its approach procedure.
TMA approach procedures are modeled as a set of machines/shops M that have to work a set of jobs A. The set of jobs A is composed by inbound flights in a selected time step.
As a consequence, minimum space separation between two consecutive aircraft is modeled as sequence dependent machine set-up time.
In such a way, the ASP is modeled as a no wait job-shop scheduling model with sequence dependent machine set-up times and job release dates.
Environment is introduced in the model in order to calculate the environmental cost, in terms of perceived noise and received pollution, on each machine M_i.

2.1 Airplane modeling

A *job* is associated to each arriving airplane. Each aircraft will fly a specific procedure p of the q available procedures $p \in \{1,\ldots,q\}$, therefore each job j is composed of a sequence of operations $O_j^1,\ldots,\ O_j^{m_p}$ where m_p is the number of operations associated to the *p-th* procedure.
Given a set A of n airplanes, waiting to land, the Air Traffic Controller's sequencing task is equivalent to find the best schedule for the n related jobs.
Since each aircraft will fly a specific procedure p, the aircraft/job set A may be partitioned into q disjoint subsets.
Therefore the set A is comprised of $(A_1,\ldots,\ A_q)$ disjoint sub-sets of aircrafts/jobs, each set flying a specific procedure p. The generic aircraft j is so considered as the job j having the following parameters:

- Entrance time t_j^e: the time at which the aircraft j enters the TMA.
- Earliest Expected Landing time t_j^{eeL}: the minimum time of landing procedure completion, see next paragraph.
- Position p: the position in which the aircraft enters the TMA, usually a fix in which the aircraft passes from the cruise flight to the approach phase.
- Category C: H, M, L.
- Emission index e: it is related to noise parameter and a pollution parameter (CO_2 per nm per n° PAX).

An aircraft flying in a holding condition, localized in the initial approach fix, waiting to start the approach procedure can be represented as a job waiting to be processed by a Job-Shop machines complex.

2.2 Airspace modeling

Airspace in the approach area is assumed to be comprised of two kinds of routes:

- routes following standard procedures
- routes resulting from vectoring

This paper deals with standard procedures, vectoring will be considered in future work.

The approach path is divided into a sequence of short aircraft trajectory segments 5 nautical miles long. Each segment h_p of the p route is represented by a machine m_{h_p} and the operation of passing through a segment is modelled as an operation $O_j^{h_p}$ of the job j on the machine m_{h_p}. The choice of subdividing the trajectory into 5 nm long segments is related to the typical space separations.

In such a way, each arrival route is modelled through a set of machines $M_p = (m_1,..., m_{m_p})$ where M_p is the set of machines of the *p-th* procedure.

The generic machine $m_{h_p} \in M_p$ has the following parameters:

- Processing time t_j^h: it is related to the time required by the aircraft *j* to fly along the segment represented by the machine m_{h_p}.
- Set-up time $s_{(j-1,j)}^h$: it is related to the minimum separation between two consecutive aircraft, *j-1* and *j*, depending on their category.
- Green sensitivity factor α_{env}^h: it depends on the position of the machine on the grid map as defined in the next section.

Since here we restrict our model to a single runway and multiple procedure case, all procedures converge in an unique descent path and in an unique runway. Therefore, all the procedures will share the machines that represent the final descent path and the runway, see Fig.1.

Consider that the processing time t_j^h may vary if ATC requires the plane j to either slow down, or speed up. This relevant topic is not considered in this work and t_j^h depends only on the aircraft category.

The Earliest Expected Landing time t_j^{eeL} can now be computed as $t_j^{eeL} = \sum_{h=1}^{m_{m_p}} t_j^h$, that is the time of arrival if the aircraft *j* starts the descent procedure immediately upon entering the fix, completing the (no wait) sequence of operations $O_j^1,..., O_j^{m_p}$ without considering any separation constraint. The actual arrival time τ_j of aircraft *j* si such that: $\tau_j \geq t_j^{eeL}$

2.3 Environment modeling

The ground is discretized by a grid of $r \times s$ elements.

In this way, the environment is modeled by a matrix *G*, each matrix element corresponding to a weight that represents its sensitivity to noise and pollution.

This weight is a “sensitivity factor” α_{env} associated to each element of the grid. It depends on: the population density ρ_{pop}, the number of sensitive buildings (such as schools

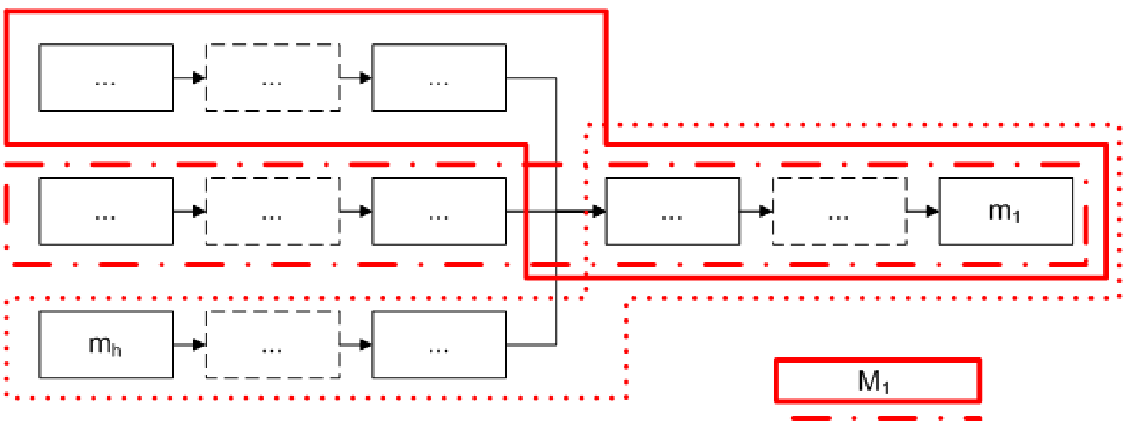

Figure 1 **The set of machines *M* is comprised of (M_1, M_2, ..., M_p) sub-sets, where M_p is the sub-set of machines of the *p*-th procedure.**

or hospitals) n_{bui} located in that grid element, cumulated noise LN_{cum} and cumulated pollution LP_{cum} over a specified time interval preceding the planned flight.

$$\alpha_{env} = f(\rho_{pop}, n_{bui}, LN_{cum}, LP_{cum}) \qquad (1)$$

The value of α_{env} for each element of the grid can vary from 0 to 1, where 0 means that the element is not sensitive to noise and pollution whereas 1 means that the element is really sensitive to environmental issues.
The proposed model takes into account values of perceived noise and received pollution as well as the impact they have on population.

2.4 ASP formulation and solution

A sequence σ = (τ_{j1} ,…, τ_{jn}) of arrival times must satisfy the set up times constraints of the last machine m_{m_p} (common to all approach procedures) that represents the runway. These time constraints represent the time separation required for each pair of consecutive arriving flights (*i* and *i+1*, *i=1,…,n-1*) and depend on the categories C_i and C_{i+1} of each a/c pair[10].

Since the set *A* of entering aircrafts/jobs is comprised of *(A_1,…, A_q)* disjoint sub-sets, each set flying a specific procedure *p*, once the sequence σ is fixed on the last common machine m_{m_p} the corresponding *(σ $_1$,…, $σ_q$)* sequences are easily determined. So it can be easily proved [10] that the minimum starting time at fix for each job following the p-th procedure is given by:

$$t_j^0 = \tau_j - \sum_{h=1}^{m_{m_p}} \left(t_j^h + s_{prec(j),j}^h \right)$$

Where prec(j)= j-1 if the machine *h* belongs only to the *p-th* procedure, otherwise is the preceding job on the common machine.

It results that the no-wait job shop model gives an initial time for the procedure which complies with all the separation constraint. It is then immediate to derive the holding time h_j for job *j*.

2.5 Genetic Algorithm

Genetic Algorithms (GA) are among the most popular evolutionary techniques that can be applied to a variety of real problems [11]. In all application domains, excellent performance expressed by the means of fast convergence times and precise results are desired. In this paper we choose elitary selection in order to provide improved convergence time.
GA exploiting elitary selection means to choose parents only among the best ranked individuals in population. This aims to quick convergence under the threat of premature convergence [12].

Each member of the population (individual) is a sequence of aircraft arrival times, these arrival times define the delay of each a/c with respect to its Earliest Expected Landing time t_j^{eeL}.

The genetic algorithm described in this paper starts running from a population of randomly generated individuals. In each iteration the fitness function of every individual in the population has to be evaluated. The algorithm fitness function prescribes the optimality of a solution so that an individual may be ranked against all the others.
The fitness function correlates closely with the algorithm's goal: it evaluates the holding time, t_h, that has to be assigned to each aircraft in order to define the landing sequence that optimizes aircraft's arrivals on the runway.
In particular the fitness function F_f is expressed as the weighted average of the holding time t_h and the total environmental factor f_{env}, as follows:

$$F_f : \rightarrow \frac{\sum_{i=1}^{n} t_{hi} * f_{env\_i}}{\sum_{i=1}^{n} f_{env\_i}} \qquad (2)$$

where i is the number of considered aircraft approaching the TMA and the coefficient f_{env} estimates the total impact that each aircraft has on the environment, made of two different contributes.

The first contribute depends on proper characteristics of the aircraft relative to the kind of propulsion system and its efficiency and to the noise emissions: we have already referred to it as emission index ***e***. The second contribute depends on the geographic position of the established holding point.

As described in the previous paragraph, the possible holding points have a fixed position that is related to the grid thus evaluating the correspondent sensitive factor α_{env}.

The total environmental factor is influenced at 80% from the emission index e and at 20% from the sensitivity factor α_{env}.

The reason of this partition lies in the fact that the altitude at which the holding is carried out only marginally influences the environmental impact we want to restrain (contain) thereby.

The algorithm terminates when the target number of generations has been achieved and it gives as output the chromosome, that is the individual with the minimum value of the fitness function.

The chromosome thus obtained corresponds to the best sequence of aircraft arrivals that maximizes the capacity of landings on the same runway.

3 Experimental Analysis

In order to test the proposed algorithm we refer to a real case study of Bologna airport terminal area.

3.1 Case study description

Bologna terminal area is a large airspace (radius about 25 nautical miles) controlled by an air traffic control centre providing ATC services to Bologna international airport (identified as LIPE according with ICAO classification).

Bologna airport has a single runway, 12/30, with a maximum capacity of 24 movements per hour. The runway is fed by a set of landing procedures. The first segment of the approach procedures starts from three initial approach fixes, FRZ, LUPOS and FER. Two additional fixes are considered, BOAN and BOAS. The fixes are the points where the holding patterns are localized.

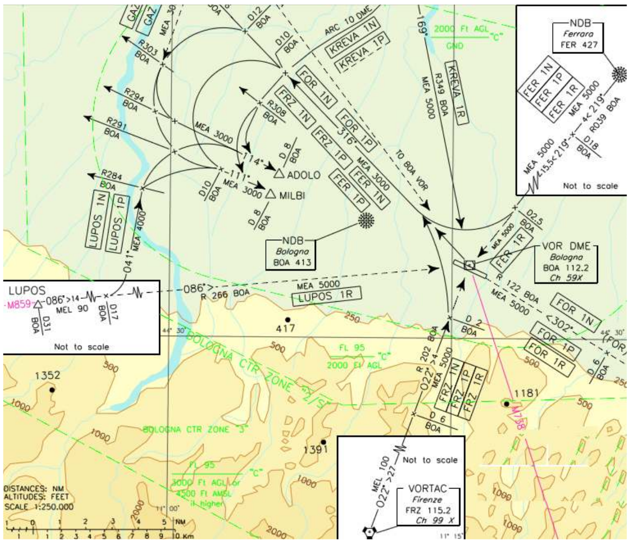

Figure 2 – LIPE Standard Arrival Routes Chart

Subdividing the standard trajectories into 5 nm long segments, we get a Job-Shop Scheduling model representation of the TMA with 20 machines.

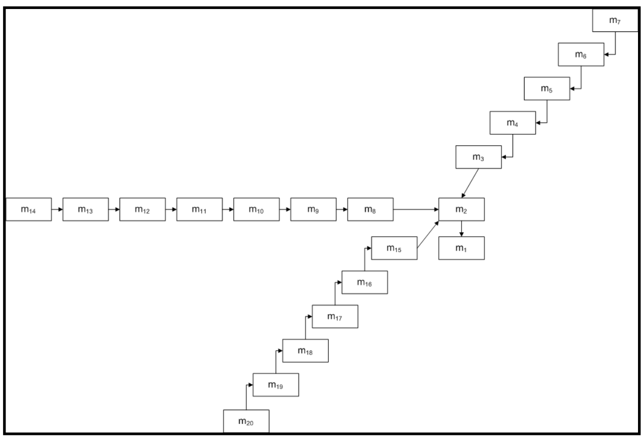

Figure 3 – The TMA's Job-Shop Scheduling model representation

The runway occupancy time can vary from 60 to 70 seconds, depending on the category (L, M, H) of the aircraft that has to land before.
We propose a real scenario data set, representing air traffic between 8:00 and 9:30 a.m. on June 1st 2010, when high traffic demand occurs, in which 25 landing aircraft are considered. The aircraft mix is 20% from category L, 80 % from category M, none from category H.

3.2 Results

The elitary GA computational time allows to solve the sequencing problem according to the on line ATC management requirements, starting from actual ATC data.
ATC data are listed in table 2: main parameters, such as entry time, expected landing time, entry fix data and category, are given for each flight.
The total environment factor is calculated as explained in the previous paragraph.
It is to notice that expected times of arrival, as reported in table 2, are not consistent. The first three flights, for example, have the same ETA (Expected Time Arrival).
In table 1 the holding time and the effective landing time are listed: 25 flights have been considered, to each flight number the holding time t_h is assigned and the ordered landing sequence is shown.
The actual landing time t_l is calculated as the sum of the initial expected time, as listed in table 2, and the holding time assigned by means of GA calculation.

Flight number	Holding time t_h	Landing time t_l
RYR4324	1	2
AFR1229	2	3
ISS656	0	9
GAC552	9	10
RYR48YR	8	13
ADR3443	0	15
RYR5544	5	16
I1240	3	18
AZA1248	6	20
DICKM	0	23
I2169	2	26
FWR18I	5	28
SAS2683	9	32
DLH6JW	9	34
RYR94Y4	11	35
AFR1528	0	44
ANE8620	0	47
VPA2332	0	54
KLM1583	4	58
AZA1311	2	62
TAP856	0	73
AZA1152	5	80
ANE8788	0	87
BAW2560	2	88
ISS695	6	91

Table 1– The landing sequence calculated for the real case study of Bologna airport terminal area.

Conclusion

In this paper the ALP has been discussed in order to face to the complex task of scheduling arriving aircraft to the available runways.
Mainly this work focuses on the minimization of delays and environmental impact, always taking into account the safety constraints dealing with the separation time between aircraft. The "green" sensitivity is defined by using numerical models.
ATC Vectors can be considered as the possibility to avoid a particular area of the Approach Air Space where the environmental impact, due to air traffic, become too heavy.
Vectors should be modeled as another machine that arrives directly on the ILS descent Path; its characteristics depend on aircraft position, altitude and type and should be evaluated by a specific trajectory optimization algorithm.
When the Vectoring Module occurs, it evaluates the possibility of changes in the sequence obtained through the vectoring into less sensitive areas.
The strength of the approach proposed lies in the possibility of giving a fast tool to air traffic controllers that is able to solve the sequencing problem according to the on-line ATC management requirements.

flight number	entry time t_e	expected landing time t_{exp}	entry fix			intermediate fix (if present)				total env. factor f_{env}	category C
			position p	altitude	speed	time	position	altitude	speed		
ADR3443	0	1	BOAN	0.8	200					1	M
RYR4324	0	1	BOAN	0.8	200					1.4	M
AFR1229	0	1	BOAN	0.8	200					1.2	M
RYR48YR	2	5	BOAN	0.8	200					1.4	M
AZA1248	2	9	FRZ	4	250	7	BOAS	0.6	220	3.4	L
RYR5544	7	11	LUPOS	3.6	250	9	BOAN	0.6	180	3.4	M
I1240	3	14	FRZ	4	250	11	BOAN	0.6	220	1.7	L
GAC552	13	15	BOAN	0.8	200					0.7	M
ISS656	13	15	BOAN	0.8	200					2.4	M
SAS2683	17	23	FER	2.5	220	21	BOAN	0.8	200	2.4	M
I2169	13	23	FRZ	4	250	20	BOAS	0.6	220	1.7	L
DLH6JW	19	24	FER	2.5	220	23	BOAN	0.8	200	2.9	M
RYR94Y4	19	24	FER	2.5	220	23	BOAN	0.8	200	3.4	M
DICKM	15	25	LUPOS	3.6	250	24	BOAN	0.6	180	1.9	L
FWR18I	17	23	FER	2.5	220	21	BOAN	0.8	200	2.4	M
ANE8620	30	44	FRZ	4	250	40	BOAS	0.6	220	2.5	M
AFR1528	38	47	LUPOS	3.6	250	43	BOAN	0.6	180	1.9	L
VPA2332	36	54	FRZ	4	250	51	BOAS	0.6	220	2.9	M
KLM1583	46	54	FER	2.5	220	51	BOAN	0.8	200	2.4	M
AZA1311	48	60	FRZ	4	250	57	BOAS	0.6	220	4.6	M
TAP856	55	73	LUPOS	3.6	250	70	BOAN	0.6	180	3.2	M
AZA1152	55	75	FRZ	4	250	71	BOAS	0.6	220	3.5	M
ANE8788	72	85	LUPOS	3.6	250	83	BOAN	0.6	180	2.7	M
BAW2560	74	86	FER	2.5	220	82	BOAN	0.8	200	3.9	M
ISS695	83	87	FRZ	4	250	85	BOAS	0.6	220	3.5	M

Table 2 – The ATC data of Bologna airport terminal area.

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