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Airport management: taxi planning*

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Abstract The Taxi Planning studies the aircraft routing and scheduling on the airport ground. This is a dynamic problem, which must be updated almost every time that a new aircraft enters or exits the system. Taxi Planning has been modelled using a linear multicommodity flow network model with side constraints and binary variables. The flow capacity constraints are used to represent the conflicts and competence between aircrafts using a given airport capacity. The "Branch and Bound" and "Fix and Relax" methodologies have been used. The computational tests have been run at the Madrid-Barajas airport, using actual data from the airport traffic.

Keywords Aircraft routing and scheduling · Taxi Planning · Airport management · Binary capacitated multicommodity flow network · Branch and Bound · Fix and Relax.

Introduction

The annual increase in the average delays of the flights is in great part a responsibility of the airport Terminal Area and the airport ground movements. The situation is even more complicated during peak hours as a result of irregular or during periods with low visibility conditions. In this event, the handling of flight ground movements is crucial to maintain the airport capacity.

The air traffic control agencies of the entire world are interested in planning tools to obtain the optimal solutions to these airport traffic problems. The aircraft ground delay represents an increasingly important part of the total flight time. The optimal use of the airport ground resources is the main motivation for this research.

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These delays are a result of the trade off between the aircraft demand and airport capacity. While the demand is growing, the airport capacity is also growing but at a slower rate. The majority of the main airports have congestion problems because of the conflicts caused by aircraft routing on the grounds of the airport.

The complexity of the problem is given by the need to model the conflicts presented between the aircrafts using the reduced capacity of the airports, especially during maximum airport congestion. The problem is not only complex because the limited capacity, but also because the strong dynamic character of the Taxi Planning. This must be considered as intensive interacting with the different airport planning modules.

The control operators and the airport designers are also interested in being able to anticipate the available airport capacity needed to attend to the ground traffic, but the users are the ones who benefit the most from good airport management, because the total flight time may be reduced by a substantial percentage. The Taxi Planning tool is not only needed in planning the airport traffic, but also as the base for any airport network design or maintenance model. Each design option would be evaluated using Taxi Planning.

Air transportation optimization models compete with simulation models in study air traffic problems, recently in Air Traffic Management and now in Taxi Planning. We are not aware of previous optimization models dealing with it. The limited literature that exists is not explicit about the methods and algorithms used to solve the Taxi Planning approaches considered.

Idris et al. (1998) researched the identification of the flow constraints that impede departure operations at major airports. It is concluded that the runway system is the key constraint and source of delay. They also proposed strategies for improving the performance of departure operations, and to determine the control points in the airport where the departure sequence at the runway can be improved. Some simplified models for different airports were presented. Pujet et al. (1999) provided a simple queuing model of busy airport departure operations. The calibration and validation of it using available runway configurations and traffic data were included.

In the works of Gotteland et al. (2000), a model based on the conflict characterization is used in the context of the pattern recognitation. They used genetic algorithms in its resolution. Anagnostakis et al. (2001) presented several possible formulations of the runway operations planning with objectives and constraints. Some properties to be used in the context of Branch and Bound were mentioned, but not concrete methodological or computational experience was mentioned. Andersson et al. (2002) proposed two simple queue models to represent the taxi-out and taxi-in processes. Idris et al. (2002) estimated the taxi-out time in terms of factors like: runway/terminal configurations, downstream restrictions and takeoff queues.

Marín and Salmerón (2003) was the first paper to include TP routing and scheduling actual formulation in terms of a binary multicommodity flow model. Marín (2004) described the Lagrangian Decomposition adaptation to solve TP. Stoica (2004) proposed an adaptive approach for the management of the aircraft available routes at the airport. Finally, Marín and Codina (2005) studied the TP network design to define the optimal airport topology in order to attend the conflicting movements of the aircrafts on it.

The Taxi Planning model presented in the paper may be identified in the mentioned context of the multicommodity flow network problems including link capacities. In this context surveys of the subject may be found in the following references: Ahuja et al. (1993), Ball et al. (1995a, 1995b). However as Taxi Planning has further side constraints (for example, node capacity constraints, and other logical constraints) and binary variables, the methods mentioned in the surveys to be applied to Taxi Planning have needed a complex adaptation.

In Section 1, the Taxi Planner problem is introduced in relation to other airport planning tools, and in relation to its dynamic character. In Section 2, the model is formulated using a space-temporal network. In Section 3, Fix and Relax, and Branch and Bound methodologies are introduced.

In Section 4, the test network is defined using data from the Madrid-Barajas airport, and the computational experiments are explained by comparing both methodologies with different scenarios. Finally, in Conclusions the main paper contributions and further researches are mentioned.

1. Taxi planning in the context of the airport management

The airport management in relation to aircraft traffic can be divided into the following planning activities: the Passenger and Baggage Management, the Parking Assignment, the Runway Aircraft Assignment, and the Taxi Planning. These activities must be located in relation to the Air Traffic Control problem at the Airport Terminal Area, and the Airport Transportation Access Network Management.

While the Parking Management assigns stands positions to aircrafts, the Runway Aircraft Assignment establishes the use of the runway slots for take-off and landing, planning the arrival and departure sequences.

Under the model point of view the best option would be to consider all of these activities in only one module, the state of mathematical models requires us to model each activity as a separate module. This requires the need for coordination between them.

This paper focuses on the Taxi Planning module, which uses data from other modules as input. These other modules have previously used Taxi Planning output for data. The different modules are involved in an outer iterative process. For example, the Departure Aircraft Runway Assignment calculates the optimal departure sequence taking the optimal trajectories on the airport ground (Taxi Planning output) as inputs. Since this last optimum does not coincide with the optimal departure sequence, an outer iterative process must make the results of both management tools do so.

Taxi Planning may be considered under different planning horizons. In short terms planning two types are studied: pre-operative and operative planning. Pre-operative planning is the orientation planning made some hours prior to the actual taxiing. Its planning time is about 1 to 2 hours, and the computational time is not critical.

Operative planning has a planning time of 15 to 30 minutes. The computational time is critical and it must be less than 1 minute, so that realistic planning is made with only a few minutes of anticipation. This is the planning horizon considered in the paper.

These plans must be integrated (especially in the operative horizon) and with the other management planning tools of the airport, updating the solution when new data becomes available.

In Taxi Planning the traffic may be classified on Take-off Traffic (TT) and Landing Traffic (LT). TT is the flight traffic from the gates to a given runway takeoff position. LT is the flight traffic from the runway exits to the gate position. In terms of this classification, we can define two basic functions:

- Landing function: Given the Landing Time and the exit runway, determine the optimal route and schedule to the gate.
- Take-off function: Given the request of authorization time from the pilot to leave the parking position, determine the optimal route and schedule to the access runway position.

1.1. Dynamic planning

Taxi Planning is also complicated because of its highly dynamic character. It considers the decisions during the planning period, but the data change in a few minutes, so solution updates are constantly needed. As new aircrafts are demanding to takeoff or land every minute, so methods with the capacity to work in almost real time are necessary.

The exact departure and arrival times are only known a few minutes in advance, so estimated and actual data must be used simultaneously at different hierarchical levels. Exact landing and take-off times depend on runway sequences, which are given by the Aircraft Runway Assignment tool. The solution is computed with uncertainty in the data and, therefore, in the results.

Uncertainty is solved using Taxi Planning output as input for the next PP, so the decisions of a planning period (PP) are data for the next one. At each iteration, a given number of flights do not get their destination at the end of the PP. These flights that may be considered are data for the next iteration and are located at the initial time of the PP of the next iteration.

2. Taxi planning networks

The Taxi Planning network is defined to represent the conflicts between flight trajectories when they use a given airport facility at the same time. These conflicts require the definition of a space-time network from an initial space network.

The conflicts may consist in link congestion, nodes that cannot be used simultaneously, links that can be used only by a limited number of flights in a given time period, etc.

The arc congestion is simulated by fictitious nodes located at the taxiways to simulate the aircraft waiting on them, and at the same time, not allowing other aircrafts to pass.

Another aspect presented in the model is the situation where a number of aircrafts try to use the same node during a given period. Other situations corresponding to other conflicts at origin and destination are taken into account, but their explicit enumeration would be very long.

2.1. Taxi planning space network

The basic space network is defined by the following space network elements: node (N) and arc (A). They define a directed graph, $\{N, A\}$.

The nodes may be classified into the following categories:

1. Parking, N^P.
2. Access runway, N^{AR}.
3. Exit runway, N^{ER}.
4. Taxiway hold, N^{TH}.
5. Ordinary (regular), N^O.
6. Fictitious, N^F.

Links arise at the following levels:

1. Between taxiway nodes.
2. Between taxiway and parking nodes.
3. Between taxiway, access and exit runway nodes.

The aircrafts (w) are defined as follows:

Landing Traffic (LT) Input:

1. Aircraft origin, exit runway, o(w) $\in N^{ER}$
2. Parking at destination, d(w) $\in N^{P}$
3. Time at origin, t(w).

LT Output:

1. Optimal LT aircraft routing and scheduling.
2. Optimal arrival to parking hour, $OAPH^{w}$.

Take-off Traffic (TT) Input:

1. Parking origin, o(w) $\in N^{P}$
2. Aircraft destination, access runway, d(w) $\in N^{AR}$
3. Time at origin, t(w).

TT Output:

1. Optimal TT aircraft routing and scheduling
2. Optimal take-off hour, OTH^{W}

2.2. Taxi planning as a space-time network

The space time network is defined by temporarily replicating the previous space network, using periods of time to divide the planning period, PP. The period set is $T = \{0, 1, \ldots, |T|\}$, where each element of T is characterized by a uniform time period, t_p. The time space graph, G^* (N^*, A^*), is defined by the replicated node set, N^*, and the space temporal links, A^*.

The TP variables are referred to as the space-temporal links, $\{(i, t), (j, t'), \forall i, j \in N, \forall t, t' \in T\}$, but taking into account that the link velocity is considered fixed in an average value, for each link, the time t_{ij} used by any flight to move along each link depends on its average velocity.

Each flight, w, is defined by an origin node, o(w), a destination node, d(w), and an origin time, t(w). In the space-time network the origin is a single node$\{o(w),\ t(w)\}$, but the destination is a set of space-temporal nodes defined by the nodes with d(w) for the different periods and the intermediate nodes between the origin and the destination during the final of the PP, if the flight doesn't arrive at the destination during the PP.

The space-time network may be represented using the following Figure 1, from the origins (O) to the destinations (D) and from the initial PP, iPP, to the final PP, fPP. The curves correspond to the aircraft trajectories in the space-time network.

Although some of the aircrafts begin and finish their trajectories during the PP, some others (a large number), given the dynamic character of TP, do not begin at their origin nodes, and others do not end at their destination node.

The variables used to define the Taxi Planning model (TP) are binary ones:

$E^{w}_{i,t} = 1$, if the aircraft *"w"* waits in node *"i"* at the period *"t"*; and 0, otherwise.
$X^{w}_{i,j,t} = 1$, if the aircraft *"w"* is routed from the node *"i"* to the node *"j"* at period *"t"*; and 0, otherwise.

TP minimizes total routing time for all the flights, so the objective function, F, is defined by the period time spent to route all the aircrafts:

$$F(X, E) = \sum_{w\in W} \sum_{t\geq t(w)} \lambda^{w} \left(\sum_{i,j\in A} t_{ij} X^{w}_{i,j,t} + \sum_{i\in N^{W}} E^{w}_{i,t} \right) + \sum_{w\in W} \sum_{i\in N} r^{w}_{i} E^{w}_{i,|T|},$$

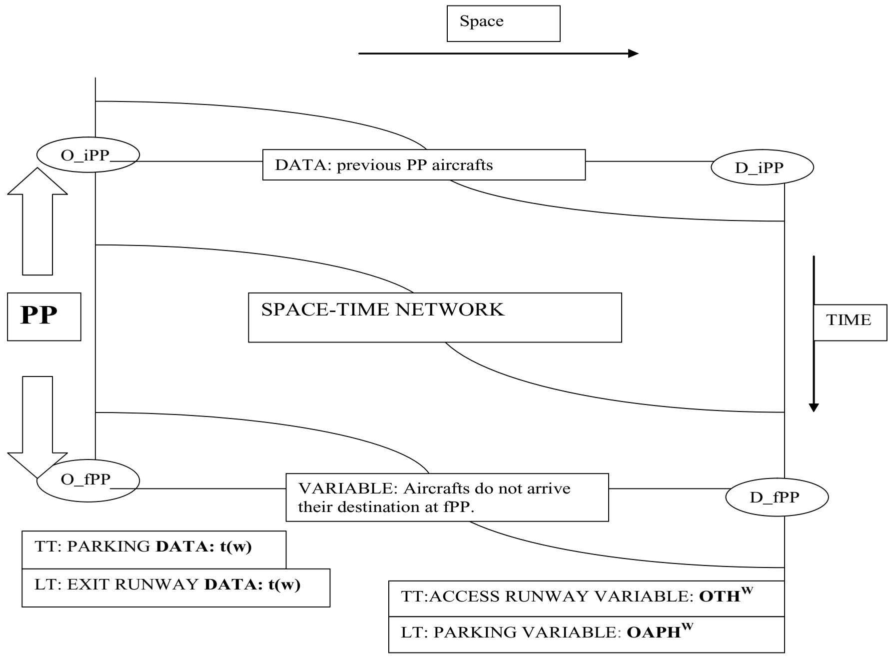

Fig. 1 Space-time basic airport scheme

where λ^w is the priority that the aircraft "w", W is the aircraft set and r_i^w is the estimated time necessary for the aircraft "w" to arrive at its destination from the node "i", located at fPP. r_i^w is obtained using a shortest path algorithm.

Other objective functions may be defined, like the delay time at link queues or waiting nodes, or the security criteria, like minimizing the number of conflicts, etc. In any case, the objective is the system optimum, which is assumed to be represented by the airport controller, who depends on the airport management, which depends on government agencies.

The TP feasible set is defined by the multicommodity flow conservation constraints, the flow capacity constraints, and other side constraints.

The flow conservation constraints at nodes are:

$$E_{i,t}^w + \sum_{j \in T^*(i)} X_{j,i,t-t_{ji}+1} = E_{i,t+1}^w + \sum_{j \in F^*(i)} X_{i,j,t+1}, \ \forall t, \forall i, \forall w$$

where the sets "From, F*", and "To, T*" are defined as:

$$F^*(i) = \{j \mid (i,j) \in A^*\}, \quad T^*(i) = \{j \mid (j,i) \in A^*\}, \ \forall i \in N^*$$

The flow node conservation constraints need to take into account the aircraft at origin node, o(w). The aircraft "w" may wait or move at (o(w), t(w)):

$$E_{o(w),t(w)}^w + \sum_{j \in F^*(o(w))} X_{o(w),j,t(w)}^w = 1, \forall w \in W$$

The same at $t = |T|$, the flights must be end waiting in some node (including the air node, if the aircraft can take off during the PP).

$$\sum_{i \in N} E_{i,|T|^w} = 1, \ \forall w \in W$$

The flow capacity constraints at nodes "i" are defined as follow:
Wait node, N^W, capacity constraints:

$$\sum_{w} e_w \, E^w_{i,t} \le capn_i, \ \forall t, \forall i \in N^{TH},$$

where $capn_i$ is the capacity (in surface units) of the node "i", and "e_w" is the surface needed for the aircraft "w" when it is waiting in a taxiway hold node.

Ordinary, N^O and exit runway, N^{ER} node capacities: The aircrafts cannot wait in these nodes.

$$E^w_{i,t} = 0, \quad \forall t < |T|, \forall i \in N^O \cup N^{ER}$$

Parking, N^P and access runway, N^{AR} node capacities are of value 1:

$$\sum_{w} E^w_{i,t} \le 1, \quad \forall t, \forall i \in N^P \cup N^{AR} \cup N^F$$

Other constraints are relative to the node capacities, as it is the case for some nodes, where the flights arriving at them during each period is limited to only one.

$$\sum_{w} E^w_{i,t} + \sum_{w} \sum_{j \in T^*(i)} X^w_{j,i,t-t_{ji}+1} \le 1, \quad \forall t, \forall i \in N^O \cup N^{AR} \cup N^F$$

Other constraints may be defined to characterize different conflicts, as is the case when we have two access nodes in the same departure runway, or certain links like the parking links that they may be used in both ways, etc. Other constraints are logical, for example, fixing the values of some variables which value must be zero, etc.

3. Methodology

The TP is a multicommodity network flow model with binary variables and side constraints, and it may be solved using methods of Binary Programming such as the method of "Branch and Bound", and "Fix and Relax".

The method more frequently used to solve integer problems without special structures is the method of "Branch-and-Bound" (B&B). To consider the properties of this methodology the following references may be consulted, Nemhauser and Wolsey (1988), and Wolsey (1998). Another method able to explore the hierarchical structures of the model is the "Fix and Relax" method. Two good references for this methodology are Dillemberger et al. (1994) and Escudero and Salmerón (2002).

Different Cplex parameters have been tested using B&B and F&R to try to improve the solution process, but the importance of these changes are minor.

3.1. Fix and relax

Using F&R to solve the TP, a natural decomposition is to use the periods of the PP (Marín and Salmerón, 2003). In the first step, the variables of the first period of PP are taken as binary and the rest are linear relaxed. In the second step, the variables of the second period are binary, while the optimal binary variables of the first step are fixed, and so on. Another possibility is to group several periods in only one step of F&R, and therefore reducing the number of steps.

Considering the TP model, its optimization variables may be described as vectors at each period in the following way:

E_t : Wait variable vector at period t: For each aircraft w and node i.
X_t : Movement variable vector at period t : For each aircraft *w* and link i,j.

The TP model may be briefly expressed in function of those variables:

$$TP: \quad Min.\ F = \sum_t f_t(\boldsymbol{E}_t, \boldsymbol{X}_t)$$

$$\text{suject to} \begin{cases} A\,\boldsymbol{E} + B\,\boldsymbol{X} = d \\ \boldsymbol{E}_t \in \{0,1\}^n, \ \forall t \\ \boldsymbol{X}_t \in \{0,1\}^m, \ \forall t \end{cases}$$

where the TP objective function is the sum of terms that depend on each period. Each one is a linear function: $f_t = c_t^E \boldsymbol{E}_t + c_t^X \boldsymbol{X}_t$. The linear constraints of TP have been represented with the help of the matrices of dimension m by n: A and B and of the vector of dimension n: d, where n and m are defined by,

$$n = \text{aircraft number} \times \text{node number}$$
$$m = \text{aircraft number} \times \text{link number}$$

The TP model for each stage "s", TP^s, is defined by the following way,

$$TP^s: \quad Min.\ F(TP^s) = \sum_t f_t(\boldsymbol{E}_t, \boldsymbol{X}_t)$$

$$\text{suject to} \begin{cases} A\,\boldsymbol{E} + B\,\boldsymbol{X} = d \\ \boldsymbol{E}_t \in \{0,1\}^n, \ \text{para } t = s \\ \boldsymbol{E}_t \in [0,1]^n, \ \text{para } t > s \\ \boldsymbol{E}_t = \hat{\boldsymbol{E}}_t, \ \text{para } t < s \\ \boldsymbol{X}_t \in \{0,1\}^m, \ \text{para } t = s \\ \boldsymbol{X}_t \in [0,1]^m, \ \text{para } t > s \\ \boldsymbol{X}_t = \hat{\boldsymbol{X}}_t, \ \text{para } t < s \end{cases}$$

Let $\hat{\boldsymbol{E}}_t$ *and* $\hat{\boldsymbol{X}}_t$ $(\forall t < s)$ be the TP^t model solution.

The Fix and Relax (F&R) algorithm for TP is defined as follows,

- *Step 1: Initialization*

Set k = 1. Solve TP^1
If TP^1 is infeasible, STOP: TP is infeasible.
Otherwise, let $F(TP^1)$ be a TP lower bound, and continue with step 2.

- *Step 2: Iteration*

Set k = k + 1. Solve TP^k
If TP^k is infeasible, STOP: TP is probably infeasible (to be sure it is necessary to solve TP by B&B).

- *Step 3: Termination*

If k = |T|, STOP: Let $F(TP^{|T|})$ be a TP upper bound and the TP solution for the optimization variables, E_t , X_t.
Otherwise, *return* to Step 2.

4. Empirical application

The Madrid-Barajas airport is the network chosen to test the TP model. It is a good example given that it has suffered annual increase in traffic of 9.81%, 17.45%, 3.51% and −0.4%, since 1998 to 2002. However the greatest problems arise during the summer, when the monthly traffic is greater than 3 million users. Aena (2004)

Several test networks have been defined to approach the Madrid-Barajas (MB) Airport. The one we present here has 8 terminals with 166 gates, an arrival runway with 4 exits, a departure runway with 2 takeoff positions, and about 56 nodes and 100 links (taxiways) between the gates and the runways, and a variable number of flights, taken from actual flight data from the MB Airport.

The MB network is shown in the following Figure 2.

The algorithms of B&B and F&R have been implemented using the context of the algebraic language GAMS and CPLEX as the optimization solver. The computer used was a Fujitsu-Siemens mobile 1,8 Ghz., with a RAM memory of 1 GB.

4.1. Computational time comparative study

The computational experiment consisted in the study of the optimal solutions of the Madrid-Barajas Airport using both methodologies (B&B and F&R), two configurations (MB1 and MB2), and different lengths of the PP.

The configuration MB1 is simpler than MB2 in the description of the terminal relations and so it has fewer nodes (and links). The number of nodes is 222. Meanwhile, MB2 has almost double the number of nodes. These extra nodes are used to define inner terminal relations. The number of periods considered in the tests is 30 and 40, each one with a time of 30 seconds per period. Four cases are designed with these two parameters.

To have a better idea of the size problem, we can obtain the variable and constraint dimensions of the MB1 network. Given a space network with 222 nodes and 452 links, assuming 40 periods (this number is easily duplicated, if we take PP of 30 minutes and t_P of 20 seconds, in this case the number of periods is 90), in the space-time network, the number of nodes is 8.880 and the number of links is 18.080. Taking 30 flights in the system, the number of binary variables is 808.800, and the number of constraints is 266.400 node flow conservation, 18.080 link flow capacity constraints, etc.

The computational results are presented on the following Table 1, where it is shown in columns: type of case, number of periods at PP, number of aircrafts, B&B results expressed by Cplex Time and Total Time, the F&R results expressed also by Cplex and Total Times, and the optimum value of the objective function.

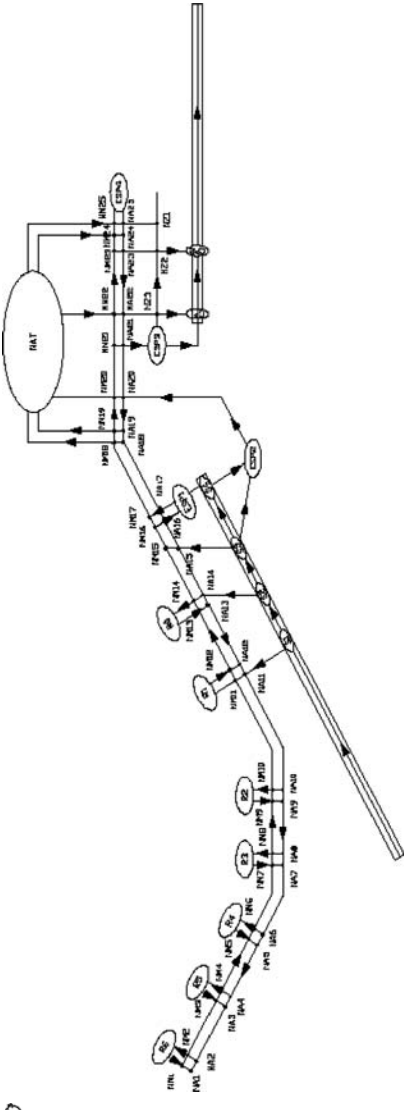

Fig. 2 TP model (MB1) of the Madrid-Barajas airport

Table 1 MB1 and MB2 Computational Results(30 and 40 periods)using B&B and F&R.

Case	|T|	|W|	B&B CPLEX secs.	B&B total time_secs	F&R CPLEX secs.	F&R total time_secs	Objective function value
MB1_30t	30	18	15	30	9,5	20	287
MB1_40t	40	21	32,9	60	21,5	50	325
MB2_30t	30	18	19	70	16,7	50	308
MB2_40t	40	21	36,7	125	27,6	110	332

F&R has been implemented using groups of 10 periods.

Several conclusions may be drawn from the test results. The total time needed to solve MB1 is about half the time needed to solve MB2, although the difference in relation to the time given by Cplex is inferior.

The results have been compared using 30 and 40 periods. Both times in the event of 40 periods are about double the events with 30 periods. This result recommends the use of fewer periods.

Finally, the results may be compared with respect to the use of B&B or F&R. F&R obtains between 10% and 40% better results than B&B, which is normal given that F&R can explore the hierarchical structure of TP.

5. Conclusions

The Taxi Planning model using a space-time network represents the conflicts and the airport congestion associated with the taxiways in the ground traffic. The model defined is a linear muticommodity flow network with large side constraints and binary variables. The Taxi Planning model defined in this paper is the first, as far as we know, to use a flow network model to simulate this problem.

The inter-relation between other airport management tools, and the strong dynamic character of the model have been studied with detail.

The computational experiment has been implemented with Madrid-Barajas Airport data taking into account different approximation degrees. The computational tests recommend the use of Fix and Relax as opposed to Branch and Bound. We can conclude that operative Taxi Planning is a difficult dynamic problem, but it can be solved in real networks with computational times of about one minute.

Further research may be aimed at completing the computational tests and the Taxi Planning model validation with real data from Madrid-Barajas airport, and the integration of the model in the context of other airport management tools. By doing this, interesting research may integrate them in combined models that simultaneously consider some of them. Other line research to be considered is the use of metaheuristics and decomposition methods to solve it. Other extension is to use Tax Planning to study airport configurations.

References

Aena Statistic Data. (2004). Madrid-Barajas airport, http://aneo.aena.es/aena.html

Ahuja, R.K., T.L. Magnanti, and J.B. Orlin. (1993). Network Flows. Prentice Hall.

Anagnostakis, I., J-P. Clarke, D. Böhme and U. Völckers. (2001). "Runway Operations Planning and Control: Sequences and Scheduling." *Journal of Aircraft* 38 (6), 988–996.

Andersson, K., F. Carr, E. Feron, and W.D. Hall. (2002). "Analysis and Modeling of Ground Operations at Hub Airports." 3nd USA/Europe Air Traffic Management R&D Seminar, Napoli, 13–167.

Ball, M.O., T.L. Magnanti, C.L. Monma and G.L. Nemhauser. (1995a). *Network Routing.* Elsevier Science B.V.

Ball, M.O., T.L. Magnanti, C.L. Monma and G.L. Nemhauser. (1995b). *Network Models.* Elsevier Science B.V.

Dillenberger, Ch., L. Escudero, A., Wollensak, and W. Zhang. (1994). "On Practical Resource Allocation For Production Planning And Scheduling With Period Overlapping Setups." *European Journal of Operational Research* 75, 275–286.

Escudero, L. and J. Salmerón. (2002). "On A Fix And Relax Framework For Large-Scale Resource-Constrained Project Scheduling." submitted to Annals of Operations Research.

Gotteland, J.B., N. Durán, J.M. Alliot and E. Page. (2000). "Aircraft Ground Traffic Optimisation.", Paper of *Ecole Nationale de l'Aviation Civile*.

Idris, H.R., B. Delcaire, I. Anagnostaki, and E. Feron, J-P. Clarke and A. R. Odoni. (1998). "Identification Of Flow Constraint And Control Points In Departure Operations At Airport Systems." Paper AIAA-98.4291 *American Institute of Aeronautics and Astronautics*.

Idris, H., J-P. Clarke, R. Bhuva and L. Kang. (2002). "Queuing Model for Taxi-Out Time Estimation." *Air Traffic Control Quarterly*, 10 (1) 1–22.

Marín, A. and J. Salmerón. (2003). "Taxi Planning. Leonardo project." Applied Mathematic Department Report, *Polytechnique University of Madrid*.

Marín, A. (2004). "Taxi Planning. Lagrangian Decomposition." submitted to *Transportation Science.*

Marín, A. and E. Codina. (2005). "Network Design: Taxi Planning." submitted to *Annals of Operations Research.*

Nemhauser, G.L. and L.A. Wolsey. (1988). *Integer and Combinatorial Optimization*, J. Wiley.

Pujet, N., B. Delcaire and E. Feron. (1999). "Input-Output Modeling And Control Of the Departure Process Of Busy Airports." Report No. ICAT-99-3. MIT International Center for Air Transportation.

Stoica C. Dragos. (2004). *Analyse, représentation et optimisation des avions sur une plate-forme aéroportuaire.* Thèse Laboratoire d'Analyse et d'Architecture des Systèmes du CNRS, *Rapport LASS 04601.*

Wolsey, L.A. (1998). *Integer Programming*. J. Wiley.