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# THE USE OF INTEGER PROGRAMMING AS A PLANNING TOOL FOR ATFM - INFRAERO'S AIRPORT NETWORK AS A CASE STUDY

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## ABSTRACT

This study uses an integer linear programming model to optimize the application of Air Traffic Flow Management (ATFM) actions such as ground holding, air holding and flight cancellation considering INFRAERO's airport network capacity. The case study investigate different low-capacity scenarios for 1 day of operations at the 19 busiest INFRAERO's airports. The work shows its potential use as a decision-support tool for air traffic service (ATS) providers, in a strategic level, in order to take flow control actions to mitigate unbalanced capacity-demand situations.

**Keywords**: Operations Research, Air Traffic Flow Management, Integer Linear Programming, Optimization, Air Traffic Control.

# 1 INTRODUCTION

Air transportation industry has witnessed, recently, a significant growth in Brazil. The economic growth experienced by the country has reflected directly towards air transportation demand. Brazilian Civil Aviation Agency's (ANAC) Statistical Yearbook (ANAC, 2013a), which compiles several national air transportation sector's indicators, brings evidences about this fact. Figure 1 shows the evolution of total number of flights from 2003 to 2012. The growth rates were always positive, reaching a peak value of 16% between 2009 and 2010. In eight years, the number of flights operating in Brazilian airports almost doubled representing a great pressure of demand over the available infrastructure.

Periods which demand exceeds the available capacity may lead system's components to decrease their level of service and therefore, yielding undesirable outcomes such as congestions, delays or even cancellations. These events may not only represent economic loss, but also, a negative impact on industry's image, especially airlines'. Therefore, the balance between capacity and demand draws continually interest for air transportation's stakeholders.

Delays and flight cancellations are indicators that may assess the impacts on the infrastructure. Figure 1 also shows how delays and cancellations varied throughout eight years in Brazil. Over the years, authorities have been working in order to keep both delays and flight cancellations to lower levels.

The sector is constantly searching for new technologies and new processes in order to provide suitable conditions for air traffic processing. They are associated with optimization of procedures and a more active system's management in order to cope up with the growth. These actions, for example, may go from anticipating potential near-saturation scenarios to even restricting, tactically, the traffic flow to saturated components.

This study uses mathematical programming in order to optimize the application of restricting traffic flow actions. The solving approach is based on the model presented by Vranas *et al.* (1994), with some adaptions and considerations for Brazilian operational conditions. The model allows the application of flow control actions such as ground holding, air holding and flight cancellations. Although it has some simplifications regarding the airspace due to its aggregated condition, the model is a potential planning and decision tool to an initial analysis at strategic level that system's agents may use.

The work brings a case study that applies the model for the 19 largest Brazilian airports that concentrate more than 80% of the air traffic in the country (regarding 2010's air traffic statistics). It embodies three different scenarios in order to verify the model's response to different low-capacity conditions at certain main airports. In addition, it investigates how the delay generated due these conditions may be transferred to other airports through network effect.

# 2 LITERATURE REVIEW

## 2.1 Air Traffic Management (ATM)

Air Traffic Management (ATM) encompasses many different systems that conducts traffic to efficient and safe flow through airports (take-off and landings) and airspace. Among the systems, Air Traffic Control (ATC) and Air Traffic Flow Management (ATFM) are the main ones. While ATC processes are related to tactical actions, having the air traffic controller (ATCo) to maintain separations according to safety instructions, ATFM concerns about strategic actions in order to solve demand-capacity imbalances (Vossen *et al.*, 2012).

According to DECEA (2013), ATM ensures safe, effective and regular flights, respecting the prevailing weather conditions and aircraft's operational limitations. Brazil, as a signatory member of the International Civil Aviation Organization (ICAO), has its air traffic methods and rules following standards and recommendations of this organization.

### 2.1.1 Air Traffic Control (ATC)

The purpose of ATC is to ensure safety, efficiency and orderly flow for air traffic.

According to Hansman and Odoni (2009), this is achieved through four basic ATC services:

- Minimum separation maintained between aircraft;
- Flight information provided by ATC such as weather and airports information and reports;
- Notification of the competent bodies regarding the need for search and rescue, and finally,
- Organization of the aircraft flow by ATC in airspace and congested airports.

## 2.2 ATFM

ATFM consists of managing actions, over a determined planning horizon, in order to prevent imbalances between air traffic demand and available capacity. Systematic flow management initiatives were initially introduced in United States after 1981 American ATCo's strike (Vossen *et al.*, 2012).

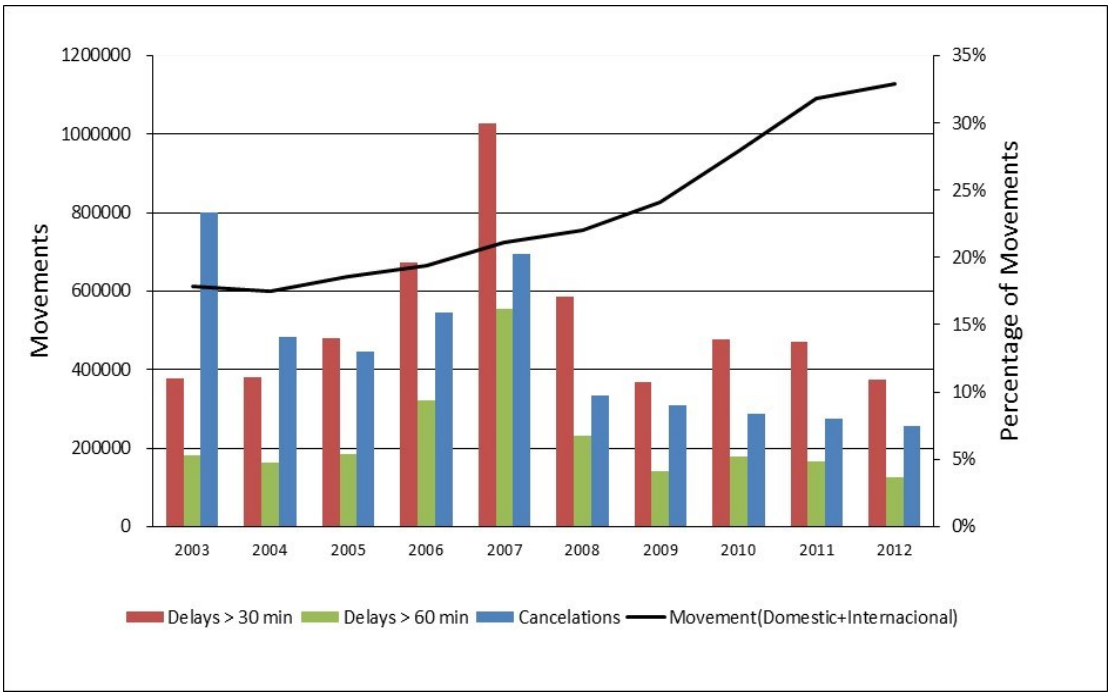



**Figure 1. Movement, delay and cancelations overview for 2003-2012 period. (ANAC, 2013a)**

By that time, in order to reduce workload of recently hired ATCos, ground-holding program was widely used. However, due to traffic growth that followed the next years, especially caused by the 1978 deregulation act, the scope of ATFM also evolved to what it is today. In Europe, due to the traffic growth experienced during late 1960s, many countries decided to create flow management centers.

These centers evolved, later, to a Central Flow Management Unit – CFMU subordinated to EUROCONTROL. According to Odoni *et al.* (2013), the development of ATFM system in the United States and Europe during 1980s and 1990s had a huge impact on ATM and airport operations. ATFM has become an essential item to keep delays within acceptable levels and to reduce airlines and other airspace users' costs. In Brazil, ATFM applications began in 1996 in order to coordinate slots for São Paulo/Congonhas Airport (SBSP) (Crespo, 2010). In 1995, the first center developed to assist ATFM applications was the Núcleo do Centro de Gerenciamento de Tráfego Aéreo (NCGNA). This center, in 2007, changed its name to Centro de Gerenciamento de Navegação Aérea (CGNA). CGNA is nowadays the government body responsible for ATFM coordination in Brazil.

In Brazil, DECEA (2013) classifies the planning horizon as:

- Strategic: it constitutes the set of actions carried out in coordination with airport service providers and aircraft operators involved in each of the predicted events,
- Pre-tactical: pre-tactical planning begins 24 hours before the use of airspace and it considers changes in aircraft and airport infrastructure, meteorological conditions and air traffic demand,
- Tactical: tactical operations consist in necessary actions before unforeseen circumstances (weather or equipment failure, for example). In addition, monitors developments in air traffic to ensure that the measures implemented have the desired effects.

### 2.2.1 ATFM Actions

ATFM acts towards controlling aircraft flow through the system's components so that the available capacity meets the traffic demand. By foreseeing possible congestion periods, ATS (Air Traffic Services) providers may take proper actions in order to adjust the rate of arrival in determined airspace's components considering their capacity. These actions deal with various segments of the flight and each one has its own characteristics with respect to planning horizon.

Some of these actions and their characteristics are summarized as follows:

- Ground holding is the establishment of a short delay on ground for aircraft that will depart to a congested airport region. Its value usually varies from 15 to 60 minutes (Vossen *et al*., 2012). It lies on the idea that the cost of delay on the ground is lesser than the delay on air, mainly due to fuel burn. Due to the strategic nature of ground-holding action, it requires a large number of meteorological information and forecast for traffic conditions,
- Rerouting consists in indicating new paths to aircraft in order to divert traffic from regions with saturated capacity or degraded weather conditions,
- Air holding is the establishment of delay for aircraft that are in the nearby region of an airport. They are conducted to follow a racetrack format path in order to be delayed a determined period. The delay is imposed on aircraft in case of heavy traffic near the destination airport. It has a tactical nature and, compared to ground holding, it is more expensive and it has a greater impact on ATCo's workload.

## 2.3 Research on ATFM

ATFM has been object of studies since late seventies. Since this problem has an intrinsic complexity, researchers have used different approaches in order to solve it such as, operations research, graph theory (Almeida *et al.*, 2008); reinforcement learning (Arruda Junior *et al.*, 2012) and artificial intelligence (Dib *et al.* 2005).

Since the scope of this work is about the use of operations research as the main tool to modeling the problem, this literature review concentrates on showing operations research approach for modeling ATFM actions.

Odoni (1987) presents the first study that addresses the problem of real time aircraft allocation in order to minimize congestion costs. This work minimizes delay impacts generated by unbalanced demand-available capacity relationship by controlling traffic flow in the various components of the traffic control system.

Initial studies presents a simple ground-holding model for a single airport (Helme, 1992; Terrab and Odoni, 1993; Richetta and Odoni; 1993). The models deal with the deterministic capacity case, i.e. capacity known in advance, and the stochastic case where the capacity is a random variable. The ground-holding problem is modelled based on an allocation problem using integer linear programming and, its objective function is to minimize the product cost caused by ground-holding delay. It is interesting to note that in these initial models, there is no concern about

air-holding delay. Authors explain this by the fact that any solution involving air holding delay would not be "optimal", representing a higher than optimal cost. This assumption may be explained by the fact that, at that time, air traffic was not congested as they are today and airports' capacity were able to handle the traffic volume.

Vranas *et al.* (1994) use the allocation problem approach but extending it to an airport network. Furthermore, it considers broader possibilities to delay allocation, which not only includes ground holding delays but also air holding delays. It also considers the possibility of flight cancellations as ATFM action in this model. The objective function is to minimize the costs with delays, assuming air holding delays are more expensive than ground holding delays. Cancellation is a drastic-choice action in this model and therefore, have cost value much higher than both type of delays. Another feature included in this model is continued flight. In other words, flights that have more than one flight legs. It allows the analysis of network effects caused by delays and cancellations.

Along the years, other airborne ATFM actions have also been included in the model using mathematical programming. Not only airports' capacity were the main concern but also airspace's capacity. Studies modelled other ATFM actions such as speed control and rerouting in order to alleviate congested air sectors (Bertsimas and Patterson, 1998; Bertsimas and Patterson, 2000). Bertsimas *et al.* (2011) raise the concern about the equity of how the model allocates delays among the airlines.

Some studies using integer programming for modeling ATFM actions in Brazil can be highlighted (Rizzi and Müller, 2002; Quaglia *et al.*, 2002). They have a modeling that is similar to the one used in the studies mentioned before. However, the models focus is mostly on ground delays. In other words, any delay that an aircraft may suffer due to saturated conditions is transferred to ground-holding delay at the departure airport.

## 3 METHODOLOGY

This work's main objective is the application of a mathematical programming as strategic planning tool for ATFM. Therefore, the approach focus on a macroscopic view of the air traffic scenario. In other words, the work's scope is focused on airports' arrival and departure rates and the effects of their variations during the day.

Vranas *et al.* (1994) model supports this work. Their model has the advantage of allowing the analysis of a large number of airports during a long period, showing its strategic characteristic. In addition, the model allows the analysis of network effects caused by delays. That is, cases of flights with multiple flight legs (continued flights). Delay on a previous flight leg may cause consequences on the next flight legs. For extreme cases, if excessive delays are necessary, cancellations may represent the only solution in order to keep movements under airport's capacity. Therefore, the modelling not only concentrates on ground-holding and air-holding delays, but also the possibility of cancellations as a flow control procedure. In addition, the modelling has some of its restrictions (equations 5 and 8) adapted to Brazilian reality, as shown by their description further in this chapter.

The work uses the modeling tool AIMMS 3.14, with the solver CPLEX 12.6.

Initially, three binary decision variables are presented for the model: $u_{ft}$ which assumes 1 if flight *f* takes-off at time *t* and 0 otherwise; $v_{ft}$which assumes 1 if flight *f* lands at time *t* and 0 otherwise; and $z_f$ which assumes 1 if flight *f* is cancelled and 0 otherwise.

The objective function represents the costs caused by delays (on ground or airborne) and cancellations applied to flights. The objective is to minimize these costs.

Before presenting the model's objective function and its restrictions, two expressions shall be defined: $g_f$ and $a_f$, expressions (1) and (2), respectively.

$$g_f = \sum_{t \in T_f^d} t u_{ft} - d_f \ , \forall f \in \mathcal{F} \qquad (1)$$

$$a_f = \sum_{t \in T_f^a} tv_{ft} - r_f - g_f \ , \forall f \in \mathcal{F} \qquad (2)$$

Where:
$\mathcal{T}$ = set of time periods *t* such that $t \in \mathcal{T}$,
$\mathcal{F}$ = set of flights *f* such that $f \in \mathcal{F}$,
$T$= set of time periods such that $t \in T$ – it is discretized in one-minute periods,
$d_f$ = scheduled departure time for flight *f*,
$r_f$ = scheduled arrival time for flight *f*,
$GH_f$= maximum number of periods for ground holding delay,
$AH_f$= maximum number of time periods for air holding delay,
$T_f^d$= allowed time interval for departure of flight *f* where $T_f^d = \{t \in \mathcal{T} \mid d_f \leq t \leq min(d_f + GH_f, max\mathcal{T})\}$,
$T_f^a$= allowable period for arrival of flight *f* where $T_f^a = \{t \in \mathcal{T} \mid r_f \leq t \leq min(r_f + GH_f + AH_f, max\mathcal{T})\}$,

Expression (1) defines the total number of ground delay periods for flight *f*. The difference between the actual time of departure, represented by the summation, and the scheduled departure time defines this delay. Analogously, expression (2) defines air delays for flight *f*. For this work, the time is discretized in one-minute periods.

After defining these two important expressions, the objective function and restriction are defined in function of them:

$$\text{Objective Function: } \min \sum_{f=1}^{F} \left[ c_f^g g_f + c_f^a a_f + M_f z_f + \left( c_f^g d_f + c_f^a (r_f - d_f) \right) z_f \right] \quad (3)$$

Subject to:

$$u_{ft}, v_{ft}, z_f \in \{0,1\} \qquad (4)$$

$$\sum_{t \in \text{TP}} \left( \sum_{f: k_f^d = k} u_{ft} + \sum_{f: k_f^a = k} v_{ft} \right) \leq Cap_{kTP} \ , \forall (k,t) \in \mathcal{K} \times \mathcal{T} \qquad (5)$$

$$z_f + \sum_{t \in T_f^a} v_{ft} = 1 \ , \ \forall f \in \mathcal{F} \qquad (6)$$

$$\sum_{t \in T_f^d} u_{ft} = \sum_{t \in T_f^a} v_{ft} \ , \ \forall f \in \mathcal{F} \qquad (7)$$

$$g_{f'} + a_{f'} - s_{f'} + (s_{f'} + r_{f'} + GH_f + 1) z_{f'} \leq g_f + (r_f + GH_f + 1) z_f \ , \forall f \in \mathcal{F}, f' \in \mathcal{F}' \qquad (8)$$

$$\sum_{t \in T_f^a} tv_{ft} - \sum_{t \in T_f^d} tu_{ft} \geq (r_f - d_f)(1 - z_f), \ \forall f \in \mathcal{F} \qquad (9)$$

Where:
$\mathcal{F}'$ = set of continued flights where $\mathcal{F}' \subset \mathcal{F}$ and *f'* $\in \mathcal{F}'$,
$c_f^a$ = cost related to 1 time period delay caused by flight *f* air holding,
$c_f^g$ = cost related to 1 time period delay caused by flight *f* ground holding,
$\mathcal{K}$=set of airports and $k \in \mathcal{K}$,
$s_{f'}$= slack time for flight *f'*,
*TP*= 60-minute period for each hour of the day,
$Cap_{kTP}$= airport k's hourly capacity (landing plus take-off) during period TP,
$k_f^d$ = departure airport for flight *f*,
$k_f^a$ = arrival airport for flight *f*,
$c_f^a$ = cost related to a 1-time-period delay caused by air holding flight *f*,
$c_f^g$ = cost related to a 1-time-period delay caused by ground holding flight *f*,
$M_f$ =flight *f*'s cancellation cost.

Expression (3) condenses the costs due to air holding, ground holding and cancellation of flight *f*. In case flight *f* only has air or ground holding delays, $z_f$ is zero, and the expression becomes $c_f^g g_f + c_f^a a_f$. In case the flight *f* is cancelled, $z_f$ is equal to one while $u_{ft}$ and $v_{ft}$ are zero. Therefore, the part of expression (3), $c_f^g g_f + c_f^a a_f$, is reduced to $-(c_f^g d_f + c_f^a r_f - c_f^a d_f)$ and it cancels out with $\left( c_f^g d_f + c_f^a (r_f - d_f) \right) z_f$ leaving only $M_f$ (cancellation cost for flight *f*).

Expression (5) indicates the airport's takeoff and landing capacity over a one-hour period. This restriction is different from the original modeling. This change was motivated by the available CGNA data concerning airport's capacity. It is defined as the number of movements per hour and accounts for landing and take-off.

Expression (6) and (7) guarantees the existence of flight *f*. In other words, it assures that if flight *f* takes-off during $T_f^d$, it will land during $T_f^a$. In case it cannot either take-off or land during the allowable time, it is cancelled.

In order to understand expression (8), the idea of slack time is defined. For a pair of continued flights (*f'*, *f*), the slack time for flight *f'* ($s_{f'}$) is the maximum delay which will not affect the next flight's departure time (flight *f*). Therefore, expression (8) assures that any delay, from a previous flight, which exceeds the slack time $s_{f'}$ will be transferred to next one. However, this excessive delay has to be less or equal to ground delay specified for flight *f*.

Also, this expression assures that if flight *f'* is cancelled, flight *f* is necessarily cancelled, as well. Vranas *et al.* (1994) mention that for continued flights in United States, the more common situation is that if flight *f'* is cancelled, the next flight *f*, is not cancelled. The flight *f* will be done using a possible spare aircraft. However, in Brazil this situation does not adhere to airlines' modus operandi. Continued flights essentially depends on the previous flight for their continuity.

Expression (9) insures that the travel length period of each flight will be, at least, equal to the scheduled one. The left-hand side of this expression yields the difference between actual arrival and departure time while the right-hand side gives the difference between scheduled arrival and departure time, in case flight *f* is not cancelled. For cancellation case, both sides of the expression will become 0.

## 4 INPUT DATA

### 4.1 Airports

The initial input data chosen for this work was restricting the airport set. By 2012, airports administrated by INFRAERO accounted for over 97% of the whole country's air traffic. Figure 2, using data gathered from 2013 Statistical Yearbook of INFRAERO (INFRAERO, 2013a), it shows that its 20 busiest airports concentrated almost 80% of the total aircraft movements performed in the entire INFRAERO's airport network. Based on this information, 19 busiest airports were selected for the study case. Campo de Marte Airport (SBMT) was not included since its traffic is mainly general aviation, which is out of this work's scope.

Another interesting characteristic from the chosen airport dataset is that important hubs are included among them such as São Paulo International Airport (SBGR) and Brasilia International Airport (SBBR), which are responsible for many connection flights. These two are important hubs, not only to Brazilian domestic flights but also to connecting international flights from and to South American countries.




**Figure 2. Overview at INFRAERO's airports movements. Source: INFRAERO (2013a).**

## 4.2 Airfield Capacity

Different conditions may affect airfield capacity such as airfield layout, airspace configuration and rules and meteorological conditions. The capacity's value may differ according to the hypothesis and operational conditions assumed during its calculations. Thus, for this work, hourly capacities used were the values presented by CGNA, shown in Table 1, the official entity responsible for airfield capacity. These values consider that hourly operations are performed in a balanced way - 50% of takeoffs and 50% of landings. SBME's hourly capacity was estimated since it was not included in CGNA (2015) database. Its capacity was estimated in 18 movements/hour.

## 4.3 Traffic Data

Concerning traffic information, ANAC's report of Scheduled Active Flights (VRA) (ANAC, 2013b) provides the necessary traffic data for the model. It contains information about regular flights: scheduled times of departure and arrival, actual times of departure and arrival, cancellations. All information extracted from this source and used in this paper is about actual times (both departure and arrival).

**Table 1. Airports' hourly capacity.**

| ICAO Code | Airport | Hourly Capacity (movements/hour) |
|---|---|---|
| **SBBH** | Belo Horizonte/Pampulha Airport | 28 |
| **SBBR** | Brasília International Airport | 50 |
| **SBCF** | Confins international Airport | 32 |
| **SBCT** | Curitiba International Airport | 38 |
| **SBCY** | Cuiabá Airport | 26 |
| **SBEG** | Manaus International Airport | 28 |
| **SBFL** | Florianópolis International Airport | 33 |
| **SBFZ** | Fortaleza international Airport | 28 |
| **SBGL** | Rio de Janeiro International Airport | 48 |
| **SBGO** | Goiânia Airport | 28 |
| **SBGR** | São Paulo International Airport | 49 |
| **SBKP** | Campinas International Airport | 31 |
| **SBME** | Macaé Airport | 18[1] |
| **SBPA** | Porto Alegre International Airport | 28 |
| **SBRF** | Recife International Airport | 28 |
| **SBRJ** | Rio de Janeiro/Santos Dumont Airport | 33 |
| **SBSP** | São Paulo/Congonhas Airport | 28 |
| **SBSV** | Salvador International Airport | 32 |
| **SBVT** | Vitória Airport | 26 |

**[1] SBME hourly capacity was estimated by the author**
**Source: CGNA (2015).**

A previous analysis was performed using a 15-day radar database (during December 2010) in order to identify the days with less actions taken by ATC, that is, trajectories with less deviations from their original pattern.

According to this analysis, the most appropriate day in this database was December 07th, 2010. Figure 3 presents the traffic pattern for the sum of all the selected airports' movement. According to it, it is possible to observe that peak hours are during morning (from 8:00 to 10:00) and evening (18:00 to 20:00). At that day, using the data extracted directly from VRA database, 2,671 flights were scheduled (taking into account only flights that departed and arrived during this day), as shown in Table 2. It is important to highlight the large number of continued flights scheduled for that day (32% out of total scheduled normal flights). Table 3 shows that five airports have more than 50% of the continued flights for that day. Although the information of continued flights are not directly present in the VRA database, these values were estimated crossing the available information in it: flights' callsign, arrival and departure airports and arrival and departure actual times.

Flights that depart from or arrive at an airport which do not belong to the data set are not part of this work's scope. However, these airports are considered as a single airport that has infinite arrival and departure capacity. This strategy has the objective of restricting

any effects that these airports may have on the airports belonging to the data set.

**Table 2. Traffic data for December 07th, 2010.**

| Flights | | % (out of Scheduled) |
|---|---|---|
| Scheduled (total) | 2,671 | - |
| Performed | 2,414 | 90.4% |
| Cancellations | 257 | 9.6% |
| Continued (total) | 853 | 32.0% |

**Source: INFRAERO (2013b).**

**Table 3. Continued flights through the airports.**

| Airport | Continued flights | %(out of total of continued flights) |
|---|---|---|
| SBGR | 109 | 12.8% |
| SBBR | 91 | 10.7% |
| SBCT | 82 | 9.6% |
| SBSV | 81 | 9.5% |
| SBGL | 70 | 8.2% |

**Source: INFRAERO (2013b).**

## 4.4 Delay costs

The model aims to minimize the cost caused by delays and cancellation imposed to flights. However, the cost of one-minute delay on ground is expected to be less costly than a one-minute airborne delay due to mainly fuel burn. Therefore, identifying how these costs are related to one another affects directly the results of the model.

Geisinger (1986) developed a study to Federal Aviation Administration (FAA) relating the costs for ground holding and air holding in order to understand financial impacts of ATFM actions on air traffic operations. He estimated that the costs for ground holding and air holding were US$591 and US$ 2.283, respectively - a ratio of 1 to 3.86. However, technological advances in the aviation field, such as improvements in engines and energy use and especially fuel value fluctuations, affect significantly this ratio.

**Table 4. Delay Costs for Strategic Delays.**

| Delay Cost per minute (€) | Ground Holding | Air Holding |
|---|---|---|
| Fuel Cost | 0.2 | 22.8 |
| Maintenance Cost | 0.6 | 1.2 |
| Crew Cost | 7.3 | 7.3 |
| Airport Taxes | 0.5 | 0.0 |
| Passenger Compensation | 17.3 | 17.3 |
| Direct cost to Airlines | 25.8 | 48.6 |
| Opportunity Cost to Passenger | 27.1 | 27.1 |
| **Total Cost** | 52.9 | 75.7 |

**Source: EUROCONTROL (2013).**

A more recent work by EUROCONTROL (2013) quantifies, similarly to Geisinger's work, these costs caused by ATFM actions. Table 4 shows that the ratio for these costs is 1 to 1.43 (comparing total cost of ground holding and air holding delays), for strategic delays. Comparing both works, it is worth noticing that the ratio between these two types of delays has decreased by a half in less than 30 years.

## 4.5 Scenarios

For this work, some scenarios were set up in order to understand, using the proposed model, how capacity reduction at certain airports during some hours affects the airport network, especially on airport with a high number of continued flights. The analysis of traffic data showed a large number of continued flights, especially in certain main airports (Table 3). Thus, any variation in capacity during some hours of the day may not affect flights locally only, but it may also generate delays or even cancellations, which will propagate throughout the whole network.

It is a well-known fact that some Brazilian airports have degraded meteorological conditions during some periods of the year. However, statistics about closed periods, airports' restrictions periods and how these conditions affect capacity are not easily available, as far as we know.

Therefore, low-capacity periods and the affected airports were assumed for this work. Then, three scenarios were set up considering hypothetical reductions in selected airport's capacity among the 19 airports. The chosen airports to have capacity restrictions are the ones presented in Table 3. Since they are processing more continued flights during the day, it is interesting to investigate how restrictions in their capacities will affect the rest of the airport network. Each scenario considers the following percentage out of maximum capacity for these airports: 90%, 50% and 0% (scenarios 1, 2 and 3, respectively). These percentages were assumed in order to represent reductions from a mild meteorological condition up to extreme conditions, which may imply in a closed airport.

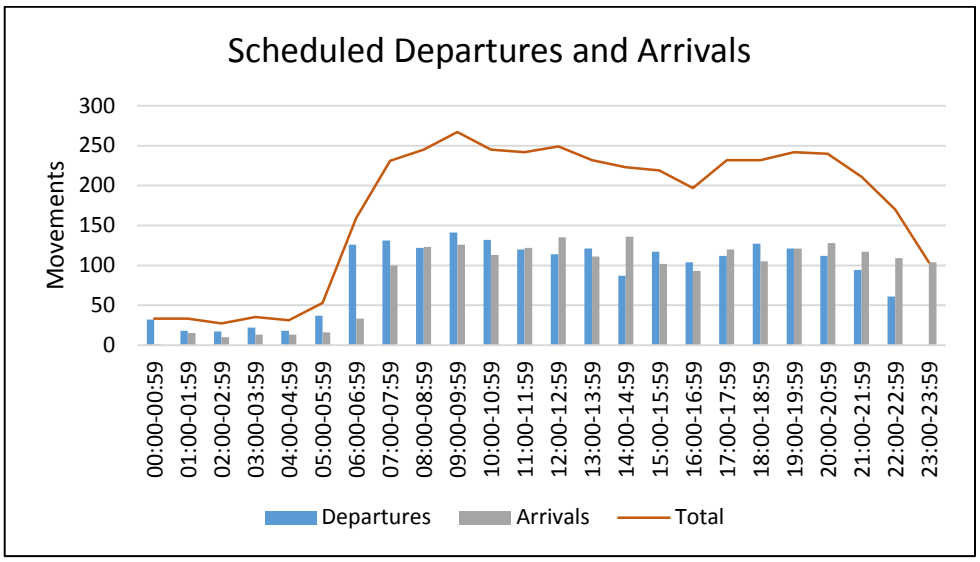



**Figure 3. Total scheduled flights at the airports set at December, 07th 2010. Source: INFRAERO (2013b).**

The delay costs for a flight were previously presented. However, these values consider the flights as a single event. However, one might argue that continued flights do not fit in this classification. Since one flight may depend on the previous one, the excessive delay of one implies on the excessive delay of the next one and so on. Therefore, delay costs for these kind of flights may not be equal to a normal flight.

Therefore, in each scenario, it will be investigated two conditions for the ratio between ground and air delays. The first condition assumes the current cost presented by EUROCONTROL (2013): 1 to 1.43 for all flights. The second condition assumes a higher cost for both ground and air delays for continued flights. Although quantifying these cost values is out of the scope of this work, for this study purpose it was arbitrarily assumed that for continued flights, this ratio doubles. This assumption comes from the idea that delays in continued flights have a chain effect for a greater number of passengers and airports. Although this ratio may be conservative, its final purpose was to show didactically the effects of delays and cancellations on these type of flights. Therefore, the ratio for air and ground delay for one-leg and continued flights is, respectively, 1.0:1.43: 2.0:2.46.

Vranas *et al.* (1994) mention that the most common maximum number of ground holding and air holding adopted in United States are 60 and 30 minutes and they are used by the authors. Although ATFM is a well-established procedure in Brazil through ICA 100-22 (DECEA, 2010), no recommendation on these maximum values was found. Thus, the values presented by Vranas *et* al. (1994) are adopted in this work.

## 5 RESULTS

Table 5 shows the number of delayed flights at each airport for all scenarios, after the optimization. This analysis allows understanding the network effects which capacity restriction may result. As mentioned before, each scenario is divided in two conditions: the first one (Same Cost) considers that normal flights and continued flights have the same delay costs and, the second one (Different Costs) considers that normal flights and continued flights have different delay costs. The five chosen airports that were subjected to capacity reductions are indicated in the first five lines. As expected, as capacity decreases for each scenario, the number of delayed flights in each of these five airports increases.

The next lines in Table 5 indicate delayed flights for others airports whose capacity were kept constant. Delayed flights are observed, even though operational conditions in those airports are kept the same. The last two lines in the same table show, respectively, the sum of affected flights for all airports and the percentage they represent, considering the whole day's movement. It is interesting to note that for the last scenario, operational restrictions in only five airports may results in impact of 21% of total flights during the day. This shows evidence of how capacity reductions may have a massive impact for the whole airport network. It is worth pointing out the case for SBSP. By 2010, it was the second largest airport (in terms of movements) in INFRAERO's airport network (INFRAERO, 2013b). Its capacity remain the same for all scenarios, but the number of delayed flights, which depart/arrive increases, confirming the network effect.

Considering the cases for different delay costs, it is possible to note that for the same scenario, this condition has little effects. In other words, imposing a different cost to continued flights (considering the double ratio, as discussed in the previous chapter), does not change the total number of delayed flights (normal flights plus continued flights) for the same scenario.

The next analysis concentrates on understanding how the optimization distributes delays for different scenarios and conditions.

Table 6 summarizes the optimization results showing how each applied ATFM action is distributed through flights. Results considering the same cost for all flights are firstly analyzed. The increasing capacity reduction (from Scenario 1 to 3), increases the number of flights delayed, as expected. It increases from about 1% (26 flights) up to 26% (698 flights) out of total flights. It is interesting to note that even in an extreme case such as scenario 3, the number of cancelled flights do not represent a high number (less than one percent out of total flights). It demonstrates how the optimization of strategical flow control actions can reschedule flights in a more efficient way.

As for scenario 1, application of ground-holding delay only shows to be enough to guarantee the traffic to meet low-capacity condition at the airports. However, as this condition gets worse, as for other scenarios, application of air-holding delays and cancellation turn out to be necessary.

Table 7 shows the average delay (ground and air delays) for normal and continued flights for optimization results. It is interesting to note that the average delay for continued flights are higher than normal flights. This is shown through the ratio presented in Table 7's last column. It can be understood as the continued flights are more affected to low-capacity conditions. This is because the flight always depend on the "previous flight". As capacity conditions deteriorates, this ratio lowers. This is caused not only because the number of delay periods decreases, but also because the number of delayed flights increases. However, as the capacity reaches a minimum, that is, it is assumed 0, the ratio increases. This is explained through the fact that the number of cancelled flights begins to increase. Therefore, in this situation, instead of using delay as an ATFM action, cancellation turn out to be the only option. Other interesting information extracted from this analysis is that the average delay for the extreme situation

(scenario 3) is 28.4 minutes per flight. An analysis of this type could be conducted in order to support possible recommendations for the application of strategic ATFM actions.

Examining the obtained results for flights with different costs, it is expected that, since the delay cost are higher for continued flights, the number of normal flights delayed get higher than the continued flights.

**Table 5. Total number of delayed flights per airport for optimized results.**

| Airport | | Delayed Flights | | | | | |
|---|---|---|---|---|---|---|---|
| | | Scenario 1 (90% capacity at 5 airports) | | Scenario2 (50% capacity at 5 airports) | | Scenario 3 (0% capacity at 5 airports) | |
| | | Same Costs | Different Costs | Same Costs | Different Costs | Same Costs | Different Costs |
| Capacity Reduction | SBBR | 2 | 3 | 20 | 23 | 64 | 64 |
| | SBCT | 3 | 3 | 19 | 19 | 44 | 44 |
| | SBGL | 1 | 1 | 4 | 6 | 48 | 48 |
| | SBGR | 1 | 1 | 27 | 24 | 87 | 86 |
| | SBSV | 0 | 0 | 2 | 1 | 39 | 39 |
| Capacity Mantained | SBBH | 0 | 0 | 0 | 0 | 6 | 6 |
| | SBCF | 3 | 3 | 5 | 5 | 25 | 25 |
| | SBCY | 0 | 0 | 1 | 1 | 13 | 12 |
| | SBEG | 0 | 0 | 1 | 0 | 14 | 14 |
| | SBFL | 1 | 1 | 1 | 1 | 10 | 10 |
| | SBFZ | 0 | 0 | 4 | 3 | 22 | 22 |
| | SBGO | 0 | 0 | 1 | 1 | 19 | 19 |
| | SBKP | 0 | 0 | 2 | 2 | 15 | 15 |
| | SBME | 0 | 0 | 0 | 0 | 3 | 3 |
| | SBPA | 2 | 2 | 4 | 3 | 37 | 37 |
| | SBRF | 0 | 0 | 3 | 3 | 34 | 34 |
| | SBRJ | 2 | 3 | 4 | 4 | 19 | 18 |
| | SBSP | 11 | 9 | 16 | 14 | 50 | 51 |
| | SBVT | 0 | 0 | 3 | 4 | 14 | 14 |
| Flights affected | | 26 | 26 | 117 | 114 | 563 | 561 |
| % out of Total | | 1.0% | 1.0% | 4.4% | 4.3% | 21.1% | 21.0% |

**Source: Author**

**Table 6. Optimization results for the scenarios (GH = Ground Holding, AH = Air Holding).**

| Scenario | Costs | Type of Flight | Ground Holding | | Air Holding | | Cancellations |
|---|---|---|---|---|---|---|---|
| | | | #Flights | Total GH (min) | #Flights | Total AH (min) | #Flights |
| 1 (90% capacity at 5 airports) | Same Costs | Normal Flights | 18 | 35 | 0 | 0 | 0 |
| | | Continued Flights | 8 | 21 | 0 | 0 | 0 |
| | Different Costs | Normal Flights | 21 | 52 | 0 | 0 | 0 |
| | | Continued Flights | 5 | 11 | 0 | 0 | 0 |
| 2 (50% capacity at 5 airports) | Same Costs | Normal Flights | 81 | 766 | 1 | 5 | 0 |
| | | Continued Flights | 49 | 447 | 1 | 2 | 0 |
| | Different Costs | Normal Flights | 98 | 1,152 | 0 | 0 | 0 |
| | | Continued Flights | 28 | 184 | 1 | 2 | 0 |
| 3 (0% capacity at 5 airports) | Same Costs | Normal Flights | 323 | 8,981 | 22 | 403 | 0 |
| | | Continued Flights | 339 | 9,812 | 14 | 199 | 27 |
| | Different Costs | Normal Flights | 323 | 8,940 | 22 | 403 | 1 |
| | | Continued Flights | 337 | 9,808 | 14 | 199 | 28 |

**Source: Author**

**Table 7. Average delay per type of flight for optimized results.**

| Scenario | Costs | Type of Flight | Average Delay per Flight (min) | Relation between continued and normal flights' average delays |
|---|---|---|---|---|
| 1 (90% capacity at 5 airports) | Same Costs | Normal Flights | 1.9 | 1.35 |
| | | Continued Flights | 2.6 | |
| | Different Costs | Normal Flights | 2.5 | 0.89 |
| | | Continued Flights | 2.2 | |
| 2 (50% capacity at 5 airports) | Same Costs | Normal Flights | 9.4 | 0.96 |
| | | Continued Flights | 9.0 | |
| | Different Costs | Normal Flights | 11.8 | 0.55 |
| | | Continued Flights | 6.4 | |
| 3 (0% capacity at 5 airports) | Same Costs | Normal Flights | 27.2 | 1.04 |
| | | Continued Flights | 28.4 | |
| | Different Costs | Normal Flights | 27.1 | 1.05 |
| | | Continued Flights | 28.5 | |

**Source: Author**

## 6 FINAL CONSIDERATIONS

Delays and cancellations are a major concern for all air transportation's stakeholders. They appear as soon as available capacity does not meet the current demand.

This work shows how ATFM actions can be optimized, using integer programming, in order to minimize these undesirable outcomes. It uses a model developed by Vranas *et al.* (1994), adapted to the Brazilian reality in order to investigate low capacity scenarios and how delay effects spread throughout the airport network. The work showed that low capacity conditions at five main airports might cause delayed flight to almost 22% of all flights during the day, for extreme cases. Obviously, in real operations, the obtained optimization results may not be as the same as presented by model. These discrepancies may appear, mainly, due to the strategic nature of this model. Sudden changes in restrictions, as for meteorological conditions as an example, may cause the model not to fully represent the current conditions.

The optimization obtained with the modelling showed in this work could be used in a strategic level, in other words, many hours before the beginning of the schedule in order to rearrange it according to limitations forecasted such as weather or airport restrictions.

For future work, this analysis can extended to other components such as air sectors, similar to Bertsimas *et al.* (2011) study, and airports' apron and runways. This analysis could focus on how these components' capacity may affect the whole airspace system.

In addition, future works could try to access CGNA information about ATFM procedures such as ground and airborne delay applied to flights. Although this information is not easily accessible, a comparison of them with results from optimization models such as the one presented in this work could lead into important analyses for ATFM field research.

## 7 REFERENCES

Almeida, C.; *et al.*(2008). *Network Flow Algorithms Applied to Air Traffic Management.* Journal of Brazilian Air Transportation Research Society. Vol4, Issue 2.

ANAC, Agência Nacional de Aviação Civil (2013a) *Anuário Estatístico do Transporte Aéreo. Dados Estatísticos e Econômicos de 2012*. Brasília.

ANAC, Agência Nacional de Aviação Civil (2013b). Histórico de Voos. Disponível em http://www2.anac.gov.br/vra/. Último acesso em 23 março de 2013.

Arruda Junior, A.; Weigang, L.; de Barros, A. (2012) *Fairness Analysis with Flight Cost Impact using the reinforcement Learning Approach.* Journal of Brazilian Air Transportation Research Society. Vol.8, Issue 1, 2012.

Bertsimas, D.; Patterson,S.S. (1998). *The Air Traffic Flow Management Problem with Enroute Capacities*. Operations Research. Vol. 46, p. 406-422.

Bertsimas, D.; Patterson,S.S. (2000). *The Traffic Flow Management Rerouting Problem in Air Traffic Control: A Dynamic Network Flow Approach*. Transportation Science. Vol. 34, No.3, p. 239-255.

Bertsimas, D.; Lulli,G.; Odoni, A. (2011). *An Integer Optimization Approach to Large-Scale Air Traffic Flow Management*. Operations Research. Vol. 59, p. 221-227.

CGNA, Centro de Gerenciamento de Tráfego Aéreo (2015). Aeroportos. Disponível em <http://www.cgna.gov.br/ > Acesso em 20 de janeiro de 2015.

Crespo, A. (2010). *Aprendizado por Reforço Aplicada ao Gerenciamento Tático do Fluxo de Tráfego Aéreo*. Masters Degree Dissertation. Universidade de Brasília.

DECEA, Departamento de Controle do Espaço Aéreo. (2010). *ICA 100-22 – Serviço de Gerenciamento de Fluxo de Tráfego Aéreo*. Brasília: DECEA, 2010.

DECEA, Departamento de Controle do Espaço Aéreo. (2013). Disponível em http://www.decea.gov.br/espaco-aereo/gerenciamento-de-trafego-aereo. Último acesso em 23 de março de 2013.

Dib, M.; Cardoso, D.; Weigang, L. (2005). *Sistema de Sincronização e Gerenciamento de Fluxo de Tráfego Aéreo Multi-Agentes.* Revista Transportes, Vol XIII, No.1, p. 48-56.

EUROCONTROL (2013), *The European Organisation for the Safety of Air Navigation. Standard inputs for EUROCONTROL cost benefit analyses*. Brussels, Eurocontrol.

Geisinger, K. (1989). *Airline delay: 1976-1986. Technical Report FAA-APO-88-13*. Federal Aviation Administration. Washington, DC.

Helme, M. (1992) *Reducing Air Traffic Delay in a Space-Time Network.* IEEE International Conference on Systems, Man and Cybernetics, Vol. 1, p. 236-342.

INFRAERO, Empresa Brasileira de Infraestrutura Aeroportuária (2013a). *Anuário Estatístico Operacional 2012*. Brasilía.

INFRAERO, Empresa Brasileira de Infraestrutura Aeroportuária. (2013b) Estatísticas.
Disponível em: < http://www.infraero.gov.br >. Acesso em: 23 março 2013.

Odoni, A. (1987). *The flow management problem in air traffic control.* NATO Advanced Research Workshop on Flow Control, Capri, Italy

Odoni, A.; de Neufville, R. (2013) *Airport Systems: Planning, Design and Management*. Editora McGrawHill.

Odoni, A., Hansman, J. (2009). *The Global Airline Industry* Edição por Peter Belobaba, Amedeo Odoni e Cynthia Barnhart. Editora John Wiley & Sons.

Quaglia, E.; André Neto; M.; Targa, D. (2002). *Um modelo de Otimização para o Planejamento de Tráfego Aéreo*. Revista Transportes, Vol X, No.2, p. 31-48,

Richetta, O.; Odoni, A.; (1993). *Solving Optimally the Static Groun-Holding Policy Problem In Air Traffic Control*. Transportation Science. Vol. 27, No. 3, p. 228-238.

Rizzi, J.; Müller, C. (2002). *Um Algoritmo de Auxílio para o Problema de Gerenciamento de Fluxo de Tráfego Aéreo*. XVI Congresso Nacional de Pesquisa e Ensino em Transportes, 2002, Natal. Anais XVI Congresso Nacional de Pesquisa e Ensino em Transportes.

Terrab, M.; Odoni, *A.* (1993). *Strategic Flow Management for Air Traffic Control*. Operations Research. Vol. 41, p. 138-152.

Vossen, T.; Hofman, R.; Murkherjee, A. (2012). *Quantitative Problem Solving Methods in the Airline Industry.* International Series in Operations Research & Management Science, Vol 169, p. 385 – 391. Editora Springer Science.

Vranas, P.; Bertsimas, D.; Odoni; A. (1994) *The multi-airport Ground-holding Problem in Air Traffic*. Operations Research. Vol. 42, No.2, p. 249-260.