FOREWORD

SBTA is an independent scientific society. Its goals are to stimulate and to advance academic and technical research applied to the air transportation industry in Brazil. Formally established in 2002, it is a nonprofit organization affiliated to the Air Transport Research Society (ATRS).

This issue of the SBTA Journal contains two articles. The two papers were selected from the many high-quality original works submitted by several researchers and professionals from the industry, the government and the academia. These two articles, authored by researchers from Boeing Research and Technology and from Brazilian Aeronautics Institute of Technology (ITA), discuss topics of great importance for the air transportation industry in the world. These two articles undoubtedly represent a significant contribution to the air transportation field in world.

The first paper describes the process created to identify and actuate on the tactical events under a CDM environment, as adopted by airlines representative’s team at the National Center of Air Navigation (CGNA), managed by the Brazilian Air Navigation Service Provider (DECEA), during a period of four months covering the FIFA World Cup 2014 operations.

The second paper 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.

João Batista Camargo Jr.
Editor-In-Chief
Guidelines for Submission of Manuscripts to the Journal of the Brazilian Air Transportation Research Society

This document summarizes the basic instructions to submit your article for publication in the Journal of the Brazilian Air Transportation Research Society.

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1) Guidelines for submission

a) Manuscript style

- The Authors' full name and affiliation must appear on the title page under the article’s title. The authors’ affiliation, full address, telephone, email and fax number must also be on this page.
- The second page must contain the article’s title, an abstract of about 100 words, and 5 key words.
- Articles must be in English, 15-25 pages in length, paper size A4, letter size 12 – Times New Roman, space between lines 1.0 and format Word, PS or PDF.
- Authors must send all figures and graphics in separate files. The figures have to be sent in high-resolution 300 dpi and gray scale files. They must be numbered (Arabic) and accompanied by the corresponding captions. All figures and tables must be referenced in the text.

b) Recommendations and reference style

- Articles should be as concise as possible and clearly present the abstract, introduction, objectives, justification and/or motivation, definition of the problem, methodology, analysis, results and conclusion, plus references;
- Authors should use the author-date system for text references and include the relevant page number if applicable.
- A list of references is required. It must contain only the works cited in the text, in alphabetical order by author. This should include the author's name, initials, year of publication in round brackets, the place of publication and publisher. For journal articles, the journal title, volume number, either month or issue number and page numbers are required.
- Copyright will belong to the Brazilian Air Transportation Research Society.

2) Article review

Your article will be reviewed by two members of the journal’s editorial board through a double-blind process.

A copy of the referees' comments will be sent to the authors for revision. For publication, the revised article must follow the guidelines above and must address the referee’s comments. Authors must state that their work has not been submitted or published elsewhere.
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COLLABORATIVE DECISION MAKING APPLIED TO THE BRAZILIAN AIR TRAFFIC FLOW MANAGEMENT CENTER - THE FIFA WORLD CUP 2014 OUTCOMES

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ABSTRACT

The Collaborative Decision Making (CDM) process under Air Traffic Management (ATM) scope is an operational management tool applied mainly at tactical and pre-tactical planning scenarios. The pre-tactical planning may also be impacted by this function up to one day before the takeoff, where actions may be taken considering the impact predicted on infrastructure and meteorological condition changes. In addition, strategic planning decisions taken based on the historical tactical actions may be used to balance capacity/demand and optimize routes for the next day of operations. This paper describes the process created to identify and actuate on the tactical events under a CDM environment, as adopted by airlines representative’s team at the National Center of Air Navigation (CGNA), managed by the Brazilian Air Navigation Service Provider (DECEA), during a period of four months covering the FIFA World Cup 2014 operations. Actions of this team consisted on negotiating tactical solutions via collaborative approach, according to the management model proposed by the International Civil Aviation Organization in Doc. 9971/AN245. Every event that produced tactical actions has been recorded, assessed their impacts on operations (in terms of minutes or fuel saved) and results analyzed through a specific model. Based on this process, significant operational cost savings have been estimated. Considering the adopted processes and methodology, potential savings of approximately US$ 5 Million per year may be obtained for the aviation industry in Brazil.

Keywords: Collaborative Decision Making (CDM), Air Traffic Management, Air Transport.
1 INTRODUCTION

According to recent studies (Oxford Economics, 2011), air traffic demand has achieved an annual growth up to 8% by the last decade in Brazil. Infrastructure investments were, unfortunately, not sufficient to support such expansion on ground, turning the airspace more and more congested and complex to manage on its operations. After a major inflight collision accident in 2006, the Brazilian Air Navigation Service Provider (DECEA) invited all airspace stakeholders (domestic airlines, airport administrators and government authorities) to setup a Collaborative Decision Making Cell in the core of Brazilian Air Navigation Management Center (CGNA), located in Rio de Janeiro. The main objective of this initiative was to optimize the tactical decisions taken, agreed among all stakeholders, in order to enhance the balance of capacity and demand of the airspace.

In fact, the concept of Collaborative Decision Making (CDM) applied by Air Traffic Flow Management was first introduced by the Federal Aviation Administration of United States (FAA) in 1990, when the Ground Delay Program (GDP) was introduced as primary tool for departures control basis. Significant savings were by the first time reported by airlines (Ball et al., 2001) on Ground Departure Procedures (GDP) using Collaborative Decision Making (CDM) processes applied on flights between San Francisco and Chicago O’Hare airports: Total savings over the initial 1½ months of prototype operations was 11,000 minutes with a value of 3 to 4 Million US$. This initiative had the primary objective to reduce air and ground delays, setting up an agreed departure sequence among stakeholders in order to promote an optimized use of airspace at high demand scenarios. The immediate consequence reported was the reduction of fuel and time related costs. Nowadays the Australian Air Navigation Service provider has implemented the most advanced CDM applied to ATM, based on the so called “business rules”, intended to provide ATC with the capability to optimize the airspace in the most efficient manner possible regarding to resources balance against needs. This allowed airspace users with the capability to optimize their networks within agreed boundaries to optimize the information sharing and, most important, to provide airport operators with better information for development of their airport master plans (Air Services Australia, 2014).

With airlines’ Operational Control Center (OCC) representatives by the first time inside the CGNA, information celerity could be enhanced among external stakeholders and company’s departments involved with flight operations, providing the basis for quick tactical decisions towards the optimum solution for the day-by-day scenarios. According to Weigang et al. (2008) e Ribeiro (2013), the information sharing between stakeholders in the decision making process is a key factor for optimized operations at this environment. The quality of information available shall be complete and updated in order to achieve a common beneficial solution for all parts, not always sharing the same interests. Some examples of tactical interventions that could be applied using such concept are: solving flight plan approval issues, exchange information regarding company’s delays impacting aprons use, inflight emergency handlings and diversions management, direct routing request management and low visibility operations. The CDM process under Air Traffic Management (ATM) scope may be seen initially as a management tool to be applied mainly at tactical and pre-tactical planning scenarios. According to the definition provided by Weigang et al. (2008) and Ribeiro (2013), the tactical planning may be considered two hours before the takeoff and end with the aircraft landing, where actions are taken mainly related to flow control management. Pre-tactical planning may be considered up to one day before the takeoff, where actions may be taken considering the impact produced by changes in infrastructure and meteorological conditions. However, as will be described, strategic planning may be
impacted by decisions taken on the tactical field, mainly related to decisions related to capacity/demand balance and route optimization. In addition, domestic airlines faced this opportunity to liaise directly with other Brazilian government entities which may also have representatives in CGNA (i.e. Brazilian Civil Aviation Agency (ANAC), Sanitary Control Agency, Federal Police, Borders Control, etc.), representing an obvious competitive advantage in terms of information flow.

In early 2012 international airlines operating in Brazil had concerning expectations regarding airspace congestion (and therefore potential increasing delays) due to the higher complexity of operations during the FIFA World Cup 2014 period, when the infrastructure and airspace element capacities were supposed to be stressed at most. The International Air Transport Association (IATA) has been therefore requested by international airlines operating in Brazil to implement in CGNA the same operational support team, already successfully implemented at FAA’s Command Center under the Collaborative Decision Making (CDM) scope, with the main objective to provide tactical support to such airline’s OCCs during the period. Attending to this request, during four months (April 2nd to July 31st 2014) forty nine foreign flag carriers operating in the country were finally represented in the Collaborative Decision Cell (CDC) in CGNA by IATA’s technical team, the so called “IATA/CGNA Liaison Desk”. In fact this was an assertive decision taken only few weeks before the event, since the Brazilian Civil Aviation Authority (ANAC) had issued strict regulations regarding slots misuse and infrastructure utilization (ANAC, 2014), which operators would need to adhere with in order to cope with infrastructure constraints, mainly at airports. In addition, collaborative assistance would be very welcome due to the airspace use plan was launched by the Brazilian Government in which airspace exclusion zones, airport coordination and diversion restrictions were adopted during the period (DECEA, 2014).

This paper is described the operational fundamentals of the IATA/CGNA Liaison Desk during the FIFA World Cup 2014 period. A methodology of data gathering and analysis is also presented in order to estimate tangible benefits derived from its operations (costs savings, fuel consumption and emissions reductions) to the aviation industry.

2 OPERATIONS SET UP

A team of six skilled technicians with aeronautical background (commercial pilots, ex-CGNA staff or dispatchers with previous experienced in airline’s Operational Control Centers, OCCs) was selected and trained in order to provide the desired level of services to airlines. Their main objective was to anticipate and identify every event that could impact on airlines operations and provide the necessary tactical information in advance to airlines in order to provide crews and dispatchers the necessary elements to take fast and correct decisions while the aircraft is inflight or even on ground. Additionally they could be able to negotiate tactical actions with other stakeholders at certain level of confidence in order to find out the best solution for problems related to restricted capacity and demand (i.e. negotiating parking spaces with airport administrators in case of diversion flights). All staff required on this duty were required to communicate fluently (written and spoken) in English and Portuguese with airlines local representatives and headquarters. This requirement is a key factor for fast and efficient communication among stakeholders supporting tactical decisions.

In order to enhance the celerity information between the desk and airlines’ OCCs, a special web portal was created with an operational alert system, in which the desk operators could quickly send messages to all registered people at airlines through a group mail. The system was able to issue five levels of alerts designed to be triggered according to the impact on operations related to the type of information provided. These are: level one (advisory information – i.e. daily briefings), level two (low impact on operations - i.e. holdings expected at terminal area), level
three (medium impact on operations which may require management level - i.e. runway closed), level four (high impact on operations which require immediate management level - i.e. airport closed due to bomb treat) and level five (catastrophic event or direct communication to airline’s high management level). The alerts level one had also the special role to provide twice a day a bulletin package (briefing format) with all relevant information related to weather, infrastructure, NOTAMs, military activities and airspace outlook evolution the next twelve hours. This information was gathered from the daily briefings performed with CGNA staff once a day.

In addition, a chat service was provided in the web portal in order to provide direct interaction between the desk operators and the airlines representatives (OCCs or local station managers). This tool was used as primary mean of communication between both. Telephone direct calls and e-mails were used as secondary means of information exchange.

3 DATA COLLECTION AND EVALUATION METHODOLOGY

All interactions between the desk staff and airlines’ OCCs or information issued that could provide tactical impact on operations were recorded daily on a specific log sheet. They could represent either the negotiation with stakeholders (CGNA and airports) in order to minimize the impact of a certain event or to provide relevant information to airlines OCCs in order for them to quickly decide what action they should take. All events were registered on a specific form (Appendix A) sent daily to IATA’s management for impact analysis. There were considered events all airlines requests (via chat, e-mails and phone contact), demand and capacity issues, unexpected events and operational alerts issued. After reported, every event was stored in a database and classified into nine distinct categories for analysis:

- **Operational (OPS):** related to flight operations issues. Most common examples were: diversions, holdings and speed-ups need due to crew duty limit time
- **Meteorological (MET):** related to climatologic issues. Most common examples were: airfield closed due to low visibility, Windshear reported by pilots, severe ice or turbulence forecast enroute, heavy rain and thunderstorm at the airport.
- **Air Traffic Control (ATC):** related to air traffic control management actions and results. Most common examples were: in-trail separations feeding terminal airspace, ground delays, arrival delays and air traffic control labor actions.
- **Infrastructure (INFRA):** related to airport infrastructure unexpected impacts. Most common examples are: closure of runways and taxiways, unscheduled work in progress, cancellation of scheduled work in progress via NOTAM and power outages.
- **Flight Safety (SAFETY):** in-flight safety related issues. Most common examples are: technical emergencies and medical diversions.
- **Security (SEC):** ground or inflight security related issues. Most common examples are: airport ground staff, police or customs labor action and un-ruled passengers.
- **Flight Plan (FPL):** flight plan processing issues. Most common examples are flight planning rejections due to erroneous flight planning filing and inflexibility of the flight planning system.
- **Operational Planning (PLAN):** events that which action performed could impact on flight planning on a period ahead. Most common examples are: negotiation of new routes during a certain period in order to avoid closed airports (by NOTAM) as reclearance alternates and creation of special waypoints in airspace in order to facilitate the flexibility of flight planning trajectories.
- **Slot coordination (SLOT):** negotiation of new slot times for delayed flights (takeoff or landings less then twelve hours from the schedule) with airport administrators and CGNA with the objective to optimize infrastructure use during the World Cup period.

After registered, the cost impact of every event was evaluated through a minute saved model, based on recent studies performed by Eurocontrol (2011) and A4A (2012). At this
proposed model three types of costs are assumed as follows:

- Minutes saved on ground: with the aircraft parked at the gate, doors open and engines shutdown, is selected the average value of 0.67 US$ per passenger per minute of delay saved. According to Eurocontrol (2011) this value corresponds approximately to the average cost of every passenger of a wide body aircraft delayed up to 30 minutes on ground considering hard and soft cost estimations. The soft cost of delay is often a dominant component in the economics of airline unpunctuality related passengers intolerance. Hard costs are due to direct factors as passenger rebooking, compensation and care. According to Eurocontrol (2011): “Although potentially difficult to ascribe to a given flight due to accounting complications, these are, in theory at least, identifiable deficits in the airline’s bottom line.” A4A (2012) assumes 39.74 US$/h the average value of passenger time in 2012, which corresponds to 0.66 US$/min, very close to the proposed value. This estimative also matches with AGIFORS (2006) which estimates passenger’s cost as 0.66 US$ per minute on ground, considering the Airbus 320 with 80% load factor on North American carriers. Wu and Caves (2000) also report 0.65 US$ per minute for average leisure passengers using the British airports.

- Minutes saved in-flight: with the aircraft moving (in-flight or taxi), doors closed and all engines running is selected the average value of 79 US$ per minute saved. This corresponds to airlines’ typical average operational hourly costs, mainly related to fuel, labor and maintenance components proposed by A4A (2012) for the United States fleet. This value also corresponds approximately to the average minute cost of a wide body en-route delay in a period of 30 min, according to Eurocontrol (2011). The assumed value is also close to the estmative of Cramer and Irgang (2007) in which an average in-flight cost of 73 US$ per minute is considered for the Boeing 737.

- Ad-hoc costs saved: related to any other consequence costs that could be saved related to an event. For the scope of this study we assumed hotel accommodation costs of 500 US$ per person (either passengers or crews, including hotel and food), aircraft parking/handling costs of 2,500 US$/hour or average ticket costs of 1,500 US$/passenger on international flights.

- Fuel saved: equivalent value of fuel saved due to operational in-flight events, such as route shortcuts and less fuel uplifted due to reserve or extra fuel reduction. The impact on fuel consumption due to weight reduction in this case was not considered on this study. The average fuel price adopted in the cost calculation model was 0.978 US$/kg (average density of 0.785 kg/l), corresponding the average world price of 122 US$/barrel up to June 2014 (IATA, 2014).

It is worthy to mention that in order to estimate the delay cost saved on ground it is necessary to have available the number of passengers on board of each flight. Since this information is very difficult to obtain directly from airlines, due to its own economic and competitive sensitivity, an average load factor was adopted according to the evaluation period considered. According to IATA (2014), the average load factor for international airlines operations in June 2014 was 79.4% in Brazil. Therefore, for calculation proposals, we assumed this average value for the period outside the FIFA World Cup 2014 Operations (from June 6th to July 20th 2014). Due to the lack of consolidated information for the World Cup period up the present date, it is assumed the hypothesis that the inbound flights would perform with approximately 90% of average load factor (bringing tourists to attend the event) and outbound flights with 50%. Considering the above assumptions, it was proposed the following general equation (1) to estimate total savings (S) obtained from the operations:

\[
S = \sum_{i=1}^{N} \text{PAX}_i \cdot (\text{FLT}_i \cdot \text{GND}, \text{DC}_\text{GND} + (\text{CLB}_i + \text{CRZ}_i + \text{DES} + \text{HOLD}) \cdot \text{DC}_\text{FLT} + \text{F}_i \cdot \text{C}_j + \text{ADHOCl})
\]
Where:
N: Total number of considered events $i$.
N$Fi$: Number of flights impacted at the event $i$.
That the total number of flights impacted at each event is verified though the approved flights list issued by the Brazilian Civil Aviation Agency (Anac), based on the impacted airline, on arrival or destination airports, by the time frame of reporting.
PAX$i$: Maximum cabin capacity for the aircraft type on airline configuration at the event $i$.
L$i$: Average load factor [%] of the flight(s) associated to the event $i$.
TTAX$ii$: Time saved during taxi in and taxi out operations [minutes].
TCL$Bi$: Time saved during climb operations [minutes].
TC$RZi$: Time saved during cruise operations [minutes].
TDES$i$: Time saved during descent operations [minutes].
THOLD$Di$: Time saved due to holding avoidance [minutes].
Fi: Total amount of extra fuel saved [kg].
DCGND: Delay cost on ground [US$ per passenger per minute of delay saved].
DCFLT: Delay cost in-flight [US$ per minute of delay saved].
ADHOC$i$: Additional costs carried out as consequence of event solution [US$].

Time saved on ground is computed based on the assumption that the time spent from the Liaison Desk operator working to sort out a related issue would be equal to the delay that pilots would experience on clearance request at the gate due to the issue not sorted. For example, during flight plan rejection events, if the desk operator takes 30 minutes to work on format errors (reported few hours in advance), then this would be computed as time saved at the gate. The same methodology was applied to new slot time events due to coordination with airports and CGNA in case of arrival or departure delays less than 12h reported by airlines during the World Cup 2014 operations. Time savings in-flight are normally related to beneficial re-routings negotiated by the desk operators upon airlines requests. Examples of impact analysis evaluation, based on the above methodology, are displayed on Appendix B.

## 4 RESULTS

Along the four months of operations, 29 foreign flag carriers (50.1% of total approved to operate in Brazil according to the Brazilian Civil Aviation Agency, ANAC) used the Liaison Desk services. In total, 1064 events were registered on which 857 (80.5%) produced savings for the industry, evaluated at US$ 6.5 Million according to the proposed estimation model. Considering the current range of the ground costs between 0.6 to 0.8 US$/min per passenger and inflight costs between 70 and 90 US$/min, the project has probably provided actual savings between 6.0 to 7.1 Millions of US$ to the industry. Three different types of actions performed by desk operators were identified in order to assist airlines:

- **Air Traffic Services assistance**: flight plan submission assistance or errors fixing, acting directly on AIS offices in order to avoiding systems rejections (2.7 % of the productive events).
- **CDM actions**: genuine negotiation of interests towards common tactical solutions between CGNA, airports and airlines (92.4% of the productive events).
- **Information provided in advance**: significant weather information or work in progress cancelled on short notice on which airlines OCCs could take quick decisions in order to minimize impact on operations (4.9% of the productive events).

Table 1 shows the breakdown of number of events, total savings and average savings of actions performed per event category, representing aggregated results from the application of the evaluation model proposed.
Table 1: Breakdown of actions per event category

<table>
<thead>
<tr>
<th>Type of Action</th>
<th>Event Category</th>
<th>GRAND TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ATC</td>
<td>FPL</td>
</tr>
<tr>
<td></td>
<td>SVG</td>
<td>AVG</td>
</tr>
<tr>
<td>Air Traffic Services Support</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDM Process</td>
<td>3</td>
<td>12,6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(92.4%)</td>
</tr>
<tr>
<td>Information in Advance</td>
<td>2</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4.9%)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>5</td>
<td>113,6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>857</td>
</tr>
</tbody>
</table>

Remarks: SVG = estimated savings (US$x1000); AVG = Average estimated savings (US$x1000); N = Number of events.

It is noticeable that CDM actions demonstrated to be the most effective source of savings whenever the synergy between airlines, CGNA and airports is present, with estimated average direct savings of US$ 7,700, corresponding to 92.4% of the total benefits obtained. Slot events during the World Cup represented 40.2% of total amount saved on this type of actions with the largest sample of data (744 events) and lowest values per unit (average US$ 3,300 per event). Planning events had significant contribution on CDM actions (42.3% of total amount saved) with the highest benefit per unit. These events, in total seven, are mainly related to previously negotiated actions with ATC impacting several flights many days ahead of the events, corresponding to 40.4% of total savings.

Operational savings, however, have the third place in contribution to CDM actions, presenting reasonably high per unit value (US$ 48,000 per event) explained by the fact that most of events are related to diversion, holdings avoided or crew duty limit avoidances (speed up and shortcuts) with implication on next leg cancellations and subsequent ad-hoc costs.

The “information in advance” type of action is mainly related to operational alerts issued, in average producing relatively low impact when compared with CDM actions. At this category ATC events produced high average benefit per event (US$ 50,000) due to one of the events representing one day coordination with CGNA for a route shortcut during the whole day, impacting on operations for all flights (with no previous flight planning implications). Infrastructure information in advance, mostly represented as construction work cancelled on short notice could save in average US$ 5,300 per event mainly because the related airport could be planned and used as alternate, permitting less fuel to be loaded during the dispatch.

Finally it is worthy to mention that 23 flight plan submission problems were fixed before clearance, related to flight plan rejections during submissions, saving in average US$5,800 per event and corresponding to approximately 2% of the total savings. During the period there were issued 742 operational alerts distributed into five categories as illustrated in Figure 1. Alerts level 2, 3, 4 and 5 were related to information in advance events. Alerts level one was used mainly for advisory information and briefings. In average 7 alerts were issued per day of operations. Level 3 and 4 alerts were used to communicate to airlines regarding important procedures regarding the World Cup operations.

Alerts were important during the last day of operations (13th and 14th July 2014) since...
special operational procedures took in place in order to ordinate the arrivals and departures at Tom Jobim International Airport, Rio de Janeiro and required the CDM process to be effective in place with all stakeholders in order to equalize the delay levels (Ground delay departure program and segregated runway operations were adopted). The sole level 5 alert was used to inform operators regarding the end of services of the Liaison Desk on 31st July 2014. Table 2 shows the number of minutes and correspondent fuel (and CO2 emissions) saved on ground and in-flight per event category. Fuel saved on ground is calculated based on time saved multiplied by an average idle taxi fuel flow of the related aircraft type on each event.

Table 2: Time and fuel saved per event

<table>
<thead>
<tr>
<th>Event Category</th>
<th>ON GROUND</th>
<th>IN-FLIGHT</th>
<th>GRAND TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time Saved per event (min)</td>
<td>Fuel Saved per event (tonnes)</td>
<td>CO2 Saved per event (tonnes)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1302.0</td>
<td>113.5</td>
<td>358.7</td>
</tr>
<tr>
<td>ATC</td>
<td>40.0</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>FPL</td>
<td>1595.0</td>
<td>39.0</td>
<td>26.6</td>
</tr>
<tr>
<td>INFRA</td>
<td>30.0</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>OPS</td>
<td>255.0</td>
<td>15.0</td>
<td>4.3</td>
</tr>
<tr>
<td>PLAN</td>
<td>8600.0</td>
<td>1229.0</td>
<td>143.3</td>
</tr>
<tr>
<td>SLOT</td>
<td>21970.0</td>
<td>30.0</td>
<td>366.2</td>
</tr>
<tr>
<td>WX</td>
<td>285.0</td>
<td>20.0</td>
<td>4.8</td>
</tr>
<tr>
<td>Sub-Total</td>
<td>32775.0</td>
<td>546.4</td>
<td>1726.0</td>
</tr>
</tbody>
</table>

Figure 2: Accumulated savings evolution
In-flight fuel saved is computed based on flight time saved multiplied to the reference cruise fuel flow for the related aircraft type, added to the extra fuel avoided on planning (if is the case). Reference fuel flow values are referenced by Peeters and Hoolhorst (2005) and respective flight operations manuals from the related aircraft on every event computed. Ground events represented 69.5% of the total time saved, mainly due to the contribution of the slots coordination. It also may be observed that fuel savings are more significant in-flight, mainly due to the planning events affecting larger number of flights. Figure 2 shows the accumulated savings evolution, according to the proposed model, along the duration of the project. The increasing benefits computed due to the slot coordination activities accomplished during the World Cup 2014 Operations period are noticeable, indeed.

5 MODEL LIMITATIONS

Since payload information of every flight is extremely difficult to obtain from airlines (considered strategic data with commercial value), the proposed model was limited to average information from the industry reports. Additionally the lack of a specific cost estimation model in Brazil lead to the adoption of a mix of European and American cost estimation models, that may not necessarily be the reality of the Brazilian industry. If considered the impact on fuel consumption due to the reduction on fuel uplift, trip fuel burned and emissions are estimated to be decreased by the same proportion. According to Fregnani et al (2013), the fuel consumption variation due to weight decrease (fuel transport factor) may require the construction of specific mathematical models as a function of aircraft type, weight, leg distance, environmental conditions and altitude, which is also information very difficult to obtain from airlines. In addition, emissions were calculated only related to CO₂ due to the major contribution of this gas on the final composition of the residuals from the jet fuel burn and equal distribution in all phases of flight.

These are limiting factors on the proposed evaluation methodology which are suggested to be revisited on further researches.

6 CONCLUSIONS AND FINAL COMMENTS

The CDM process established during the Liaison Desk operations demonstrated to be very effective during the FIFA World Cup 2014 Operations period (approximately 80% of effectiveness on actions was observed) bringing significant savings for the industry according to the proposed model of evaluation. Under this perspective, average savings of US$ 7,600 or 2.6 ton of fuel per event were estimated. Considering the results obtained the proposed operational process adopted has the potential to save approximately US$ 5 Million per year for the airlines operating in Brazil.. This corresponds to a potential of approximately 2,024 ton of fuel saved or 6,396 ton of CO₂ emissions reduced per year. It is worthy to mention that although the Liaison Desk operations was initially designed to perform on tactical solutions (mainly operations in-flight) the experience has shown that savings may be more significant whenever the solutions are negotiated impacting the planning horizon, once a larger number of flights may be influenced.

Under the World Cup 2014 Operations scope, slots coordination among airlines, airports and CGNA had also demonstrated to be very effective and provided significant impact on final results, representing 37.6% on total estimated savings. On tactical information in advance regarding infrastructure and ATC actions demonstrated to be effective for airlines OCCs in order to elect the correct decisions in-flight. This research may be used as reference for implementation of CDM in real operations of CGNA. The future work would include a more detailed analytic model for the study.
7 ACKNOWLEDGEMENTS

The author would like to thank the International Air Transport Association (IATA) for supporting this paper with data. It is worthy to mention that the author worked for this institution during the period of FIFA World Cup 2014 Operations.

8 REFERENCES


## Appendix A – Events Registration Form Sample

### DAILY EVENTS REPORT

Period: 30MAY-2100Z to 31MAY-0900Z

<table>
<thead>
<tr>
<th>TIME (Z)</th>
<th>FLT#</th>
<th>Aircraft type</th>
<th>DEP STA</th>
<th>ARR STA</th>
<th>DETAILED DESCRIPTION</th>
<th>ACTIONS ADOPTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:30</td>
<td>XXXX</td>
<td>332</td>
<td>SBNT</td>
<td>LPPT</td>
<td>ANAC REQUESTED LIAISON DESK TO CONTACT OPERATOR. FLIGHT DELAYED DUE TO AOG (MAY IMPACT TERMINATION OF SBNT COMMERCIAL OPERATIONS)</td>
<td>TP005 TOOK OFF FROM LPPT DELAYED DUE MAINTENANCE. ETD03:15 - ATD09:00Z</td>
</tr>
<tr>
<td>03:00</td>
<td>XXXX</td>
<td>738</td>
<td>MIA</td>
<td>MAO</td>
<td>ACFB BROKEN WITH LADG GEAR COLLAPSED ON RUNWAY (02:15Z - 07:30Z). FLIGHT DIVERTED TO SBBV</td>
<td>SENT ALERT LEVEL 3 AND OPERATOR CONTACTED. DESK ASSISTED ON RETURN FPL</td>
</tr>
<tr>
<td>05:00</td>
<td>XXXX</td>
<td>738</td>
<td>MIA</td>
<td>MAO</td>
<td>SBEG STILL IMPRACTICABLE</td>
<td>SENT ALERT LEVEL 3 AND OPERATOR CONTACTED</td>
</tr>
<tr>
<td>07:30</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>SBEG NORMAL CONDITIONS LANDINGS AND ARRIVALS</td>
<td>SENT ALERT LEVEL 3 AND OPERATOR CONTACTED</td>
</tr>
<tr>
<td>07:30</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>SBEG BELOW MINIMA DUE FOG</td>
<td>SENT ALERT LEVEL 2 AND OPERATOR CONTACTED</td>
</tr>
<tr>
<td>07:45</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>SBEG LANDINGS IFR</td>
<td>SENT ALERT LEVEL 2 AND OPERATOR CONTACTED</td>
</tr>
<tr>
<td>08:40</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>SBCT LANDINGS ILS CATII</td>
<td>SENT ALERT LEVEL 2 AND OPERATOR CONTACTED</td>
</tr>
</tbody>
</table>

### Events to Report:

1. Every interaction with airlines – requests, suggestions, e-mails, operational alerts, etc…
2. Holdings.
3. Diversions.
4. Takeoff delays.
5. Flight Plan issues.
6. Airport Issues
7. NOTAMs
8. Every significant event that impact operations.
9. Alerts Level 2,3,4 and 5

### IMPORTANT REMARKS

1. PLEASE INCLUDE DETAILS AS MUCH AS POSSIBLE. THIS REPORT IS VERY IMPORTANT TO MEASURE THE EFFICIENCY OF DESK OPERATIONS.
2. DO NOT REPLICATE INFORMATION ALREADY AVAILABLE IN THE AERONAUTICAL NETWORK. HOWEVER PROVIDED IN ADVANCE!
<table>
<thead>
<tr>
<th>DATE</th>
<th>FLT#</th>
<th>ACFT</th>
<th>AIR STA</th>
<th>DETAILED DESCRIPTION</th>
<th>ACTIONS</th>
<th>IMPACT</th>
<th>SAVINGS PER FLIGHT</th>
<th>SAVINGS (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14abr/14</td>
<td>XXXX</td>
<td>77W</td>
<td>GRU</td>
<td>EK Reported systematic delays on BK202 due to FPL approvals. Monitoring BK202/GRU/DXB. Delayed STD/0225Z/EDT0305Z.</td>
<td>FPL contacted. No ATC reason reported.</td>
<td>285</td>
<td>79.4%</td>
<td>-</td>
</tr>
<tr>
<td>14abr/14</td>
<td>XXXX</td>
<td>77W</td>
<td>GRU</td>
<td>EK Reported systematic delays on BK202 due to FPL approvals. Monitoring BK202/GRU/DXB. Delayed STD/0225Z/EDT0305Z.</td>
<td>FPL contacted. No ATC reason reported.</td>
<td>285</td>
<td>79.4%</td>
<td>-</td>
</tr>
<tr>
<td>16abr/14</td>
<td>SSA</td>
<td>SSA</td>
<td></td>
<td>POLICE FORCES STRIKE AT SALVADOR (SSA). Security issues may be in place at Salvador.</td>
<td>Sent IOP Alert Level 3. Coordinated with SBAZ ACC that all flights through UZ1 may be authorized for direct heading LONAS – TIM if requested by pilots, saving 3 minutes flight time.</td>
<td>218</td>
<td>79.4%</td>
<td>-</td>
</tr>
<tr>
<td>17abr/14</td>
<td>XXXX</td>
<td>332</td>
<td>LIS</td>
<td>NOTAM K0333/14 requests deviation near Cayene FIR. Valid until 30APR14 (will be cancelled due to the new preferential routes).</td>
<td>Coordinated with SBAZ ACC that all flights through UZ1 may be authorized for direct heading LONAS – TIM if requested by pilots, saving 3 minutes flight time.</td>
<td>0</td>
<td>946</td>
<td>$98,592.00</td>
</tr>
<tr>
<td>18abr/14</td>
<td>GRU</td>
<td>SSA</td>
<td></td>
<td>Police Forces Strike in Salvador (SSA) is over. Airport and Airspace operations are normal.</td>
<td>Sent IOP Alert Level 2. Coordinated with SBAZ ACC that all flights through UZ1 may be authorized for direct heading LONAS – TIM if requested by pilots, saving 3 minutes flight time.</td>
<td>0</td>
<td>30</td>
<td>$2,370.00</td>
</tr>
<tr>
<td>19abr/14</td>
<td>CNF</td>
<td>CNF</td>
<td></td>
<td>SBGF NOT AVAILABLE AS ALTERNATE. WIP POSTERION TL 30APR14. Check NOTAM K0330/14.</td>
<td>Sent IOP Alert Level 3. Coordinated with SBAZ ACC that all flights through UZ1 may be authorized for direct heading LONAS – TIM if requested by pilots, saving 3 minutes flight time.</td>
<td>0</td>
<td>49</td>
<td>$2,370.00</td>
</tr>
<tr>
<td>19abr/14</td>
<td>XXXX</td>
<td>763</td>
<td>AMI</td>
<td>MAO AIRPORT CLOSED DU TO FOG LC01741 Diverted to SBBV (unavoidable).</td>
<td>Sent IOP Alert Level 2. Coordinated with SBAZ ACC that all flights through UZ1 may be authorized for direct heading LONAS – TIM if requested by pilots, saving 3 minutes flight time.</td>
<td>0</td>
<td>1</td>
<td>$2,370.00</td>
</tr>
<tr>
<td>19abr/14</td>
<td>XXXX</td>
<td>772</td>
<td>BVI</td>
<td>Fast turn around on ground in BVI. FPL approval expedited for offwlth 20 min.</td>
<td>Sent IOP Alert Level 2. Coordinated with SBAZ ACC that all flights through UZ1 may be authorized for direct heading LONAS – TIM if requested by pilots, saving 3 minutes flight time.</td>
<td>0</td>
<td>30</td>
<td>$2,370.00</td>
</tr>
<tr>
<td>20abr/14</td>
<td>FPA</td>
<td>FPA</td>
<td></td>
<td>ROA WIP (0345-0850 - SUP AP200) SUSPENDED 19 and 20 ONLY.</td>
<td>Sent IOP Alert Level 2. Coordinated with SBAZ ACC that all flights through UZ1 may be authorized for direct heading LONAS – TIM if requested by pilots, saving 3 minutes flight time.</td>
<td>0</td>
<td>1</td>
<td>$2,370.00</td>
</tr>
<tr>
<td>20abr/14</td>
<td>XXXX</td>
<td>77W</td>
<td>GRU</td>
<td>FPL Monitoring</td>
<td>FPL Monitoring</td>
<td>$2,370.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Appendix B – Impact Analysis Evaluation Examples
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 adaptations 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)](image)

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.

Odoi (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 Odoi, 1993; Richetta and Odoi; 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 was 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.

$$g_f = \sum_{t \in T_f} t u_{ft} - d_f, \forall f \in F$$ (1)
\[ a_f = \sum_{t \in T_f} tv_{ft} - \tau_f - g_f , \forall f \in F \]  
\[ (2) \]

Where:
- \( T \) = set of time periods \( t \) such that \( t \in T \),
- \( F \) = set of flights \( f \) such that \( f \in F \),
- \( T \) = set of time periods such that \( t \in T \) – it is discretized in one-minute periods,
- \( d_f \) = scheduled departure time for flight \( f \),
- \( \tau_f \) = 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,
- \( T_d^f \) = allowed time interval for departure of flight \( f \) where \( T_d^f = \{ t \in T \mid d_f \leq t \leq \min(d_f + GH_f, \max(T)) \} \),
- \( T_a^f \) = allowable period for arrival of flight \( f \) where \( T_a^f = \{ t \in T \mid \tau_f \leq t \leq \min(\tau_f + GH_f + AH_f, \max(T)) \} \).

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:

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

Subject to:
- \( u_{ft}, v_{ft}, z_f \in \{0,1\} \)
- \[ \sum_{t \in T_f} (\sum_{f: k_f^t = k} u_{ft} + \sum_{f: k_f^t = k} v_{ft}) \leq Cap_{kTP}, \forall (k,t) \in K \times T \]
\[ (5) \]
- \[ z_f + \sum_{t \in T_f} v_{ft} = 1 , \forall f \in F \]
\[ (6) \]
- \[ \sum_{t \in T_f} u_{ft} = \sum_{t \in T_f} v_{ft} , \forall f \in F \]
\[ (7) \]

\[ g_f' + a_f' + s_f' + (s_f' + r_f' + GH_f + 1)z_f' \leq g_f + (r_f + GH_f + 1)z_f , \forall f \in F, f' \in F' \]
\[ (8) \]
\[ \sum_{t \in T_f} tv_{ft} - \sum_{t \in T_f} tu_{ft} \geq (\tau_f - d_f)(1 - z_f) , \forall f \in F \]
\[ (9) \]

Where:
- \( F' \) = set of continued flights where \( F' \subset F \) and \( f' \in F' \),
- \( c_f^a \) = 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,
- \( KH = \)set of airports and \( k \in K \),
- \( s_f' \) = slack time for flight \( f' \),
- \( TP = 60\text{-minute period for each hour of the day,} \)
- \( Cap_{kTP} = \) airport \( k \)’s hourly capacity (landing plus take-off) during period \( TP \),
- \( d_f \) = departure airport for flight \( f \),
- \( a_f \) = 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 \( c_f^a g_f + c_f^a a_f \). 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), \( c_f^a g_f + c_f^a a_f \), is reduced to \(- \left( c_f^a d_f + c_f^a (r_f - d_f) \right) \) and it cancels out with \( \left( c_f^a d_f + c_f^a (r_f - d_f) \right) \), 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 \( T_f^d \). 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.

<table>
<thead>
<tr>
<th>ICAO Code</th>
<th>Airport</th>
<th>Hourly Capacity (movements/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBBH</td>
<td>Belo Horizonte/Pampulha Airport</td>
<td>28</td>
</tr>
<tr>
<td>SBBR</td>
<td>Brasilia International Airport</td>
<td>50</td>
</tr>
<tr>
<td>SBCF</td>
<td>Confins International Airport</td>
<td>32</td>
</tr>
<tr>
<td>SBCT</td>
<td>Curitiba International Airport</td>
<td>38</td>
</tr>
<tr>
<td>SBCY</td>
<td>Cuiabá Airport</td>
<td>26</td>
</tr>
<tr>
<td>SBEG</td>
<td>Manaus International Airport</td>
<td>28</td>
</tr>
<tr>
<td>SBFL</td>
<td>Florianópolis International Airport</td>
<td>33</td>
</tr>
<tr>
<td>SBFZ</td>
<td>Fortaleza International Airport</td>
<td>28</td>
</tr>
<tr>
<td>SBGL</td>
<td>Rio de Janeiro International Airport</td>
<td>48</td>
</tr>
<tr>
<td>SBGO</td>
<td>Goiânia Airport</td>
<td>28</td>
</tr>
</tbody>
</table>

SBME hourly capacity was estimated by the author.

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>
<thead>
<tr>
<th>Flights</th>
<th>% (out of Scheduled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduled (total)</td>
<td>2,671</td>
</tr>
<tr>
<td>Performed</td>
<td>2,414</td>
</tr>
<tr>
<td>Cancellations</td>
<td>257</td>
</tr>
<tr>
<td>Continued (total)</td>
<td>853</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Airport</th>
<th>Continued flights</th>
<th>% (out of total of continued flights)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBGR</td>
<td>109</td>
<td>12.8%</td>
</tr>
<tr>
<td>SBBR</td>
<td>91</td>
<td>10.7%</td>
</tr>
<tr>
<td>SBCT</td>
<td>82</td>
<td>9.6%</td>
</tr>
<tr>
<td>SBSV</td>
<td>81</td>
<td>9.5%</td>
</tr>
<tr>
<td>SBGL</td>
<td>70</td>
<td>8.2%</td>
</tr>
</tbody>
</table>

Table 3. Continued flights through the airports.

Table 4. Delay Costs for Strategic Delays.

<table>
<thead>
<tr>
<th>Delay Cost per minute (€)</th>
<th>Ground Holding</th>
<th>Air Holding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cost</td>
<td>0.2</td>
<td>22.8</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>0.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Crew Cost</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Airport Taxes</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Passenger Compensation</td>
<td>17.3</td>
<td>17.3</td>
</tr>
<tr>
<td>Direct cost to Airlines</td>
<td>25.8</td>
<td>48.6</td>
</tr>
<tr>
<td>Opportunity Cost to Passenger</td>
<td>27.1</td>
<td>27.1</td>
</tr>
</tbody>
</table>

Total Cost 52.9 75.7


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.

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.

![Scheduled Departures and Arrivals](image)

**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 into 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 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 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.

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

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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

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

<table>
<thead>
<tr>
<th>Airport</th>
<th>Delayed Flights</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenario 1 (90% capacity at 5 airports)</td>
</tr>
<tr>
<td></td>
<td>Same Costs</td>
</tr>
<tr>
<td>SBBR</td>
<td>2</td>
</tr>
<tr>
<td>SBCT</td>
<td>3</td>
</tr>
<tr>
<td>SBGL</td>
<td>1</td>
</tr>
<tr>
<td>SBGR</td>
<td>1</td>
</tr>
<tr>
<td>SBSV</td>
<td>0</td>
</tr>
<tr>
<td>SBBH</td>
<td>0</td>
</tr>
<tr>
<td>SBCF</td>
<td>3</td>
</tr>
<tr>
<td>SBCY</td>
<td>0</td>
</tr>
<tr>
<td>SBEG</td>
<td>0</td>
</tr>
<tr>
<td>SBFL</td>
<td>1</td>
</tr>
<tr>
<td>SBFZ</td>
<td>0</td>
</tr>
<tr>
<td>SBGO</td>
<td>0</td>
</tr>
<tr>
<td>SBKP</td>
<td>0</td>
</tr>
<tr>
<td>SBME</td>
<td>0</td>
</tr>
<tr>
<td>SBPA</td>
<td>2</td>
</tr>
<tr>
<td>SBRF</td>
<td>0</td>
</tr>
<tr>
<td>SBRJ</td>
<td>2</td>
</tr>
<tr>
<td>SBSP</td>
<td>11</td>
</tr>
<tr>
<td>SBVT</td>
<td>0</td>
</tr>
<tr>
<td>Flights affected</td>
<td>26</td>
</tr>
<tr>
<td>% out of Total</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Costs</th>
<th>Type of Flight</th>
<th>Ground Holding</th>
<th>Air Holding</th>
<th>Cancellations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>#Flights</td>
<td>Total GH (min)</td>
<td>#Flights</td>
</tr>
<tr>
<td>1 (90% capacity at 5 airports)</td>
<td>Same Costs</td>
<td>Normal Flights</td>
<td>18</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continued Flights</td>
<td>8</td>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Different Costs</td>
<td>Normal Flights</td>
<td>21</td>
<td>52</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continued Flights</td>
<td>5</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>2 (50% capacity at 5 airports)</td>
<td>Same Costs</td>
<td>Normal Flights</td>
<td>81</td>
<td>766</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continued Flights</td>
<td>49</td>
<td>447</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Different Costs</td>
<td>Normal Flights</td>
<td>98</td>
<td>1,152</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continued Flights</td>
<td>28</td>
<td>184</td>
<td>1</td>
</tr>
<tr>
<td>3 (0% capacity at 5 airports)</td>
<td>Same Costs</td>
<td>Normal Flights</td>
<td>323</td>
<td>8,981</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continued Flights</td>
<td>339</td>
<td>9,812</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Different Costs</td>
<td>Normal Flights</td>
<td>323</td>
<td>8,940</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continued Flights</td>
<td>337</td>
<td>9,808</td>
<td>14</td>
</tr>
</tbody>
</table>

Source: Author

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

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

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


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


