# QUANTIFYING IMPACTS ON AIRPORT OPERATIONS CONSIDERING CONSTRAINED EN-ROUTE SECTORS

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## ABSTRACT

This paper investigates the impacts of en-route meteorological formations on air traffic operations. The study uses an optimization approach to issue flow control actions to flights in order to mitigate the effects of low-capacity moments in en-route air sectors. Three different low-capacity scenarios are set up and the number of delays and cancellations imposed due to the flow-control actions are used as metrics to evaluate the impacts. The study was able to quantify the impacts caused by these adverse weather conditions and to show how their impacts differ depending on the constrained condition presented.

**Keywords**: meteorological impacts, air traffic, air traffic flow management, optimization, air sectors

## 1. INTRODUCTION

The growth of air transportation demand has been following an upward trend worldwide in the latest years. Major aircraft companies' demand forecasts converge that for the next 20-year period, the number of aircraft will practically double (Boeing, 2015; Airbus, 2015). This growth will be more intense in emerging markets, with forecasted growth of 5.8% per year (Airbus, 2015). Improving current systems and processes may figure an alternative action to cope up with this growing-demand scenario, delays and cancellations.

A particular factor, which is of special concern for air traffic operations stakeholders due to the great impact on air traffic operations, is the necessity of improvement in air traffic operations during convective weather. According to Clarke et al. (2012), convective weather can be defined as a stochastic phenomenon, which, in severe cases, may prevent the aircraft to operate. Song, Greenbaum and Wanke (2009) mention that the severe weather increases air traffic controllers' (ATCos) workload and lowers the number of aircraft that they could handle simultaneously in that sector. In this cases, the air sector's is restricted to a smaller portion of it, which compresses traffic and makes more difficult for ATCos to maintain standard minimum separation between aircraft.

In order to avoid disruptions and minimize the undesirable outcomes, which these scenarios may cause to air traffic (e.g. delays and cancellations), different flow-control actions may be taken by air traffic service providers (ATSP). These actions are applied in different flight phases: keeping flights in air holding patterns, rerouting through longer paths to avoid the affected regions, changing the flights to different altitudes that may not be the optimal, keeping aircraft on ground longer times (ground holding), etc. Due to their different timings regarding planning and implementation, varying from a tactical to a strategical nature, a factor, which makes it more complicated for ATSP, is the great level of uncertainty intrinsic to the convective weather and its effects on sector capacity. This may lead to situation where a constrained region may disappear before the planned set of flow-control actions is over which may result in underused air sector capacity. In addition, the inverse situation, where a sudden decrease of air sector capacity may yield a large amount of air delays and cancellations.

This paper focus on studying how the effects of different levels of en-route convective weather may affect the air traffic flow. The levels of convective weather are indirectly measured according to their effects on air sector's capacity (intense convective weather cause greater decrease in capacity while milder ones affect lesser). The study uses a dynamic optimization approach to issue different flow-control actions in different flight stages considering three different levels of constrained capacity en-route sectors. The number of actions taken using this approach for each scenario are used as a metric to measure the impacts generated by the degraded weather conditions.

## 2. LITERATURE REVIEW

### 2.1. Air sector capacity

Although this study's scope does not include methods for calculation of air sector capacity, it presents a short review on the subject and the current method used in Brazil by its aeronautical authority.

The air sector capacity can be defined as the maximum number of aircraft enter in a volume of airspace and transit without having to be diverted to another volume of airspace or to an airport during a fixed amount of time (Clarke et al., 2012). In addition, capacity can be seen as an indicator of ATCos' workload threshold. However since the it is not only in function of number of aircraft but the complexity present by the traffic, it may not be represent by only a single value, even in clear weather (Song, Greenbaum and Wanke, 2009). Therefore, different studies have been done in order to capture some nuances which traffic complexity bring to the workload (Hunter and Ramamoorthy, 2005; Zobell, Wanke, and Song, 2006; Martin, Evans, and DeLaura (2006); Song, Greenbaum and Wanke, 2009; Clarke et al., 2012).

Figure 1 shows, using real data, how the observed number of aircraft crossing determined sector varies according to blocking space (weather coverage) caused by the severe weather. It shows that sector capacity does not hold a linear relationship with the weather coverage. This shows evidences that more than just one factor influence on the final value of capacity.

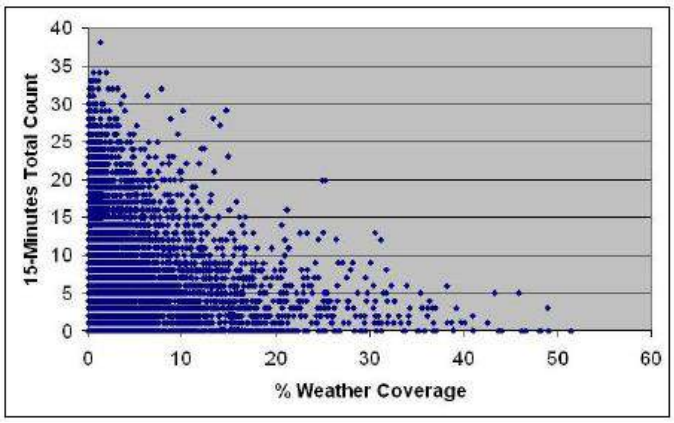



**Figure 1: Sector throughput for different weather coverages. Source: Song, Greenbaum and Wanke (2009).**

In Brazil, the aeronautical authority responsible by the airspace administration is the Department of Airspace Control (DECEA) and it has its own method to calculate air sector capacity. In its document "MCA 100-17 Capacidade de Setor ATC", it uses an equation, which embodies different factors affecting capacity, such as the time ATCo spend on commucations between flights, the size of the sector and total time the flights spends inside the sector, the workload that imposed to the ATCo due to traffic complexity.

### 2.2. Air traffic services

Air traffic control services are provided to flights in controlled areas in order to maintain the established minimum separations between aircraft and keep the fluidity of air traffic (DECEA, 2009).

The definition of minimum separation has two purposes regarding safety. The first one refers to the ATSP's accuracy has in localizing a determined aircraft. In some regions, due to the radar's update rate, it may yield in a greater uncertainty of the aircraft's position. This results in a necessity of maintaining a bigger separation between aircraft. The second one refers to the effects of wake turbulence generated by each aircraft. According to DECEA (2009), it results in three effects: violent shaking, loss of altitude or ascending speed and stress on its structure.

The aircraft are classified in three categories (DECEA, 2009):

- Heavy (H): All kinds of aircraft which have maximum takeoff weight (MTOW) more or equal to 136.000 kg (300.000 lb)
- Medium (M): All kinds of aircraft which have MTOW varying from 7.000 kg (15.500 lb) to 136.000 kg (300.00 lb)
- Light (L): All kinds of aircraft which has MTOW lower than 7.000 kg (15.500 lb)

Table 1 shows radar minimum separation criteria and the separation in for takeoff, according to the possible pair of aircraft.

**Table 1. Minimum separation criteria.**

| Radar separation | Preceding aircraft | Following aircraft | Separation (NM) | Separation during takeoff | Preceding aircraft | Following aircraft | Separation (seconds) |
|---|---|---|---|---|---|---|---|
| | **Heavy (H)** | H | 4 | | **Heavy (H)** | H | 60 |
| | | M | 5 | | | M | 120 |
| | | L | 6 | | | L | 120 |
| | **Medium (M)** | H | 3 | | **Medium (M)** | H | 60 |
| | | M | 3 | | | M | 60 |
| | | L | 5 | | | L | 120 |
| | **Light (L)** | H | 3 | | **Light (L)** | H | 60 |
| | | M | 3 | | | M | 60 |
| | | L | 3 | | | L | 60 |

**Source: Adapted from DECEA (2009)**

The air traffic management (ATM) comprises several systems that help flights to accomplish their takeoffs and landings, and to travel safely through aerospace. Among the systems, it worth noting the air traffic control (ATC) and air traffic flow management (ATFM).

The ATM is implemented in order to ensure safe, regular and efficient flights, respecting current weather conditions and aircraft's operational limitations (DECEA, 2013). Brazil, as a state member of the International Civil Aviation Organization (ICAO), has its own air traffic methods and rules, which follow the rules and recommendations of this organization.

Due to the air traffic growth, there are moments that demand may exceed available capacity in certain system components, such as in certain regions of airspace or airports. In order to reduce delay and its propagation throughout the system, flow-control actions are taken in order to manage and coordinate the aircraft flow through airspace sectors. These set of actions are make the Air Traffic Control Flow Management (ATFM). According to Odoni et al. (2013), the development of ATFM systems in the United States and Europe in the 1980s and 1990s had an enormous impact on the ATM and airport operations. The ATFM has become an essential item to keep delays within acceptable levels and reduce costs for airlines and other airspace users. It can be applied in three phases of planning (DECEA, 2013): strategic, pre-tactical and tactical.

ATFM actions has as primary objective controlling aircraft flow through components of the system so that the available capacity and traffic demand are brought to a balance. By identifying periods when a possible congestion may appear, actions are taken. They can be applied in different parts of the flight control center airspace and always yield the same result, but with different characteristics:

- Ground-holding: it is the amount of delay established to flights at origin airports, before their takeoff, when its forescated congestion period at destination airport during their arrival;
- Rerouting: it is the indication of new paths to the way aircraft to divert traffic regions with saturated capacity or degraded weather conditions;
- Air holding: it is imposed on aircraft in case of heavy traffic near the destination airport in order to coordinate the sequencing of aircraft during the arrival. The aircraft are

maintain at certain altitudes performing a racetrack pattern (holding pattern) while wait clearance to proceed the destination airport;

- Sequencing: it is the establishment of takeoffs and landings in order to guarantee that the traffic follow the appropriate separation minima. This strategy is strongly influenced by the operational rules and the traffic mix considered;

- Alternative Standard Arrival Routes (STAR): it consists of allocating the flights for different arrival routes which haves similar shapes but different travel times. This action helps to replace the use of holding patterns and Murça and Müller (2013) suggest it as a way of arrival sequencing.

Figure 2 shows a visual layout of the techniques described above and that may be applied along the trajectory of the aircraft.

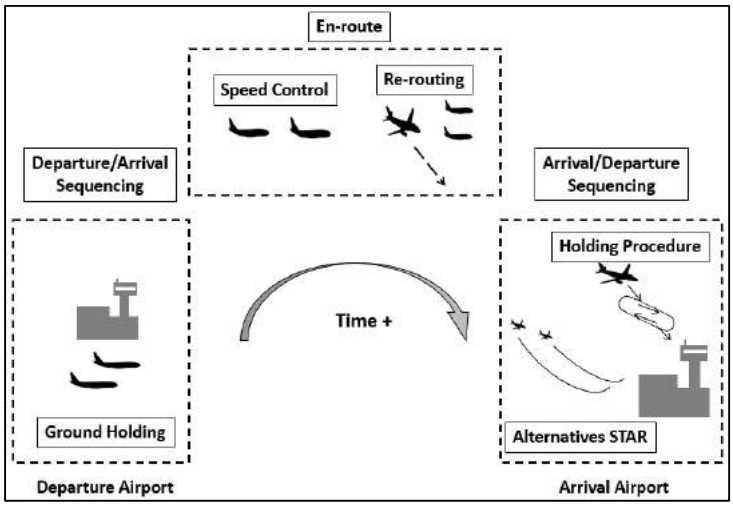



**Figure 2: ATFM actions in different flight phases.**

## 3. METHODOLOGY

The optimization approach used in this study to determine the ATFM actions applied in different parts of the flight uses mixed integer linear programming. The modeling aggregates the application of ground-holding measures, rerouting and speed control, the idea of sequencing and alternatives STARs. In other words, the aircraft have the ability to absorb delays or advances during the en-route phase, or even before takeoff.

The model is based on the modeling proposed by Augustin et al. (2012) and the capacity constraints of the original modeling were replaced by the sequencing constraints of landing, takeoff and landing followed takeoff, based on the formulations made by Beasley et al. (2004), Dias et al. (2010) and Murça and Müller (2013).

The model's general idea is to minimize the overall delay for each flight: each minute of delay applied to each flight represent a cost and the objective function is to minimize the total cost. The model was solved by Paragon Decision Technologies AIMMS 3.14 optimization program, using the CPLEX solver 12.6. The following components summarizes the model synthetically, presenting the objective function and constraints' description:

- Objective function

    - Penalization for
        - Cancellations
        - Use of alternative routes
        - Late arrival at certain waypoint
        - Time variation between two waypoints (speed variation)
        - Variation in total trip time (increasing or decreasing)
        - Number of periods of ground holding
- Subject to
    - Restrictions in sequencing
        - Landing/landing
        - Takeoff/takeoff
        - Landing/takeoff
    - Restriction regarding flight structure
    - Restriction regarding delays

The model uses a dynamic approach for its solving. It divides the total period of analysis in shorter periods and the parameters for each of these periods are constantly being updated for each optimization run. The different flight phases, especially the sequencing of arrival and departure, has a dynamic characteristic. They can be impacted by different inside and outside factor regarding the air traffic system such as delays on airport's landside, flight cancellations, adverse atmospheric conditions, etc. Some of these factors have predictability limited to a large time horizon while some of them are practically unpredictable. Therefore, the constant update of current conditions, which support ATSP's decision for ATFM application and, it make the decisions more adherent to the reality.

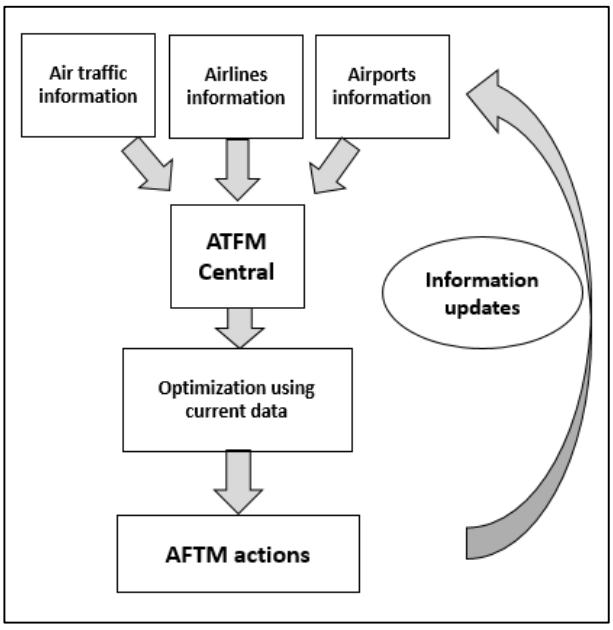



**Figure 3: Scheme for optimization process.**

### 3.1.1. Data and materials

In this study, four main airports were chosen to be part of the study: São Paulo International Airport (SBGR), São Paulo/Congonhas Airport (SBSP), Brasília International Airport (SBBR) and

Campinas Airport (SBKP). These first three represented, in 2012, the first, second and third largest airports in Brazil, considering number of movements (ANAC, 2013).

Also it was considered the en-route air sectors connecting these airports. They belong to the FIR Brasília, they busiest FIR in Brazil in 2013 (CGNA, 2014). Figure 4 show schematically the location of each one of the 7 sectors considered and Table 1 brings their full capacity value provided by DECEA.

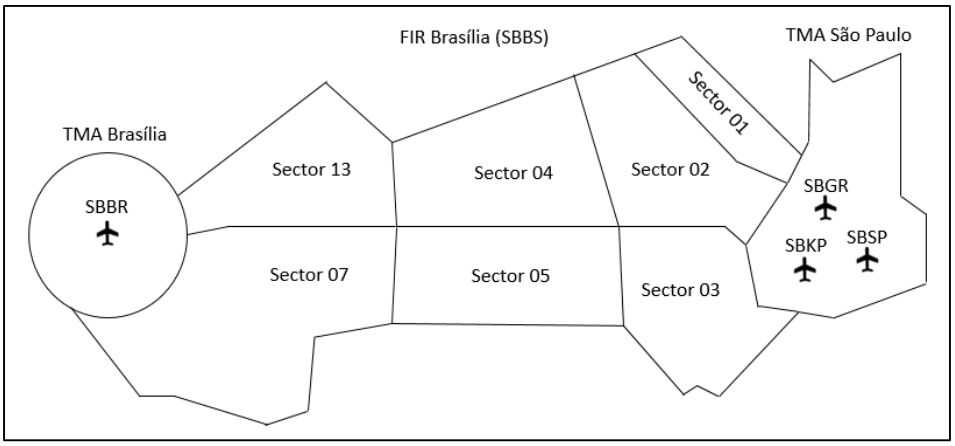



**Figure 4: Sectors in the studied region.**

**Table 1: Sectors capacity.**

| Sector | Capacity (Number of aircraft) |
|---|---|
| 01 | 14 |
| 02 | 12 |
| 03 | 14 |
| 04 | 14 |
| 05 | 14 |
| 07 | 16 |
| 13 | 14 |

**Fonte: DECEA (2014b)**

Flight information were obtained from a database which embodies a total of 15 day of operations in these airports, from December 15$^{th}$ to December 31$^{st}$, 2013. For this work, it was chosen 4 hours of the busiest day, December 20$^{th}$, from 10:00 to 14:00. This period has a movement of 512 flights

Separations for landing operations shall ensure that, for the release of a landing, there should be another aircraft performing the landing approach at a distance of 5 NM. Since there is no actual data about the approach speeds of aircraft, an average of speeds was used for each aircraft, provided by the manufacturer (BOEING, 2011). Assuming the average speeds approaching 145.3 knots, the time between landings should be 2 minutes.

The model's objective function minimizes the costs of delays or cancellations taxes on aircraft. Thus, it is necessary to define cost figures for the delays caused by ground holding, air holding. The EUROCONTROL develops studies yearly that estimates the costs of the delays for both strategic actions (ground holding) and tactical actions (air holding).

The final costs are broken down into contributing factors, as shown in Table 3. It can be seen that the cost of ground holding are around 70% of the air holding. In Brazil, there are no studies, as far we know, which bring the values for these costs. Thus, the modeling will be used the costs estimated by EUROCONTROL.

**Table 2 – Description of costs.**

| Delay cost per minute (€) | Ground-Holding | Air-Holding |
|---|---|---|
| **Fuel cost** | 0.2 | 22.8 |
| **Maintenance** | 0.6 | 1.2 |
| **Crew costs** | 7.3 | 7.3 |
| **Airport taxes** | 0.5 | 0 |
| **Passenger compensation** | 17.3 | 17.3 |
| **Airlines direct costs** | 25.8 | 48.6 |
| **Passenger' cost of oportunity** | 27.1 | 27.1 |
| **Total costs** | 52.9 | 75.7 |

**Source: EUROCONTROL (2013)**

### 3.2. Scenarios

For this work, it was set three different scenarios of air sector capacity. It is possible to observe in Figure 4 that the sector 2 and sector 3 are the closer ones to SBGR, SBSP and SBKP. Flights arriving/departing to/from these three airports have to fly through them. Therefore, they have a great importance in the operations of these three airports.

In order to study how the effects of severe weather can cause to the airports, three scenarios were developed considering these two sectors. The first scenario, SCN01, considers the sectors with full capacity, or in other words, operations in a clear weather condition. The second scenario, SCN02, considers the sectors with 90% of their full capacity. This decrease in capacity represents an intermediate weather formation affecting these sectors. Finally, SCN03 considers that their capacity drops to 80% of their full value. This would represent a severe meteorological condition, which may strongly impact the airport's operation. The values used in the scenarios were based on the interviews with experienced ATCos which suggested that 80 % was a high level constrained capacity during operations.

## 4. RESULTS

The obtained results for these three scenarios are presented in Table 3. They show the different ATFM actions applied in each one the scenarios, braking it down according to each type of action. It interesting to note that the number of mostly all number of the actions increase from SCN01 to SCN03. This is can be explained by the fact that ATSP have to apply these action in order to keep the constant traffic for the airports.

Regarding ground holding, there is an increase of 63% in the number of minutes, from SCN01 to SCN03, that the flight are hold on the ground before departure. This is an interesting fact because since the flights are kept on ground, they are using excessively apron positions. In extreme conditions, this situation might influence severely on operations if the airport does not have enough apron positions.

Other fact that it is interesting to point out from the obtained results is the increase of number of actions regarding speed variation from SC01 to SC03. There is an increase of about 4 times the initial value in SC01. These actions are required by ATCos during en-route phases and may represent an increase of workload for them due to the higher complexity for a more constrained scenario.

Regarding the costs, the objective function yields an indirect way to measure how the severe affects this subject, since it is made of costs of each type of action taken, as seen in the previous section. It can be seen that there is an increase of almost 45 % in the value of the objective function for a decrease of 20% of air capacity.

The action with least variation among all is the number of flights using alternative STARs. This can be explained by the fact that most of action are taken before the flight arrives for sequencing, during en-route or in the origin airport. Therefore, this type of action is not necessary to maintain the flights close to the scheduled arrival time as the other actions.

**Table 3: Result for ATFM actions applied in each scenario.**

| Scenarios | | SC01 | SC02 | SC03 |
|---|---|---|---|---|
| Ground holding (min) | | 35 | 45 | 57 |
| Speed Variation | Delays (min) | 3 | 6 | 24 |
| | Advances (min) | 25 | 44 | 78 |
| Travel time variation | Delays (min) | 66 | 64 | 62 |
| | Advances (min) | 10 | 20 | 30 |
| Alternative Star (flights) | | 11 | 12 | 13 |
| Objective Function | | 657.75 | 738.60 | 948.35 |

Figure 5 and Figure 6 the number of aircraft, each minute, in sectors 02 and 03, respectively. It can be seen that the most affected sector is sector 02 for the different scenarios. There is a substantial decrease in the number of aircraft for periods from 11:100 to 12:20 while in sector 03 the moments is kept unchanged.

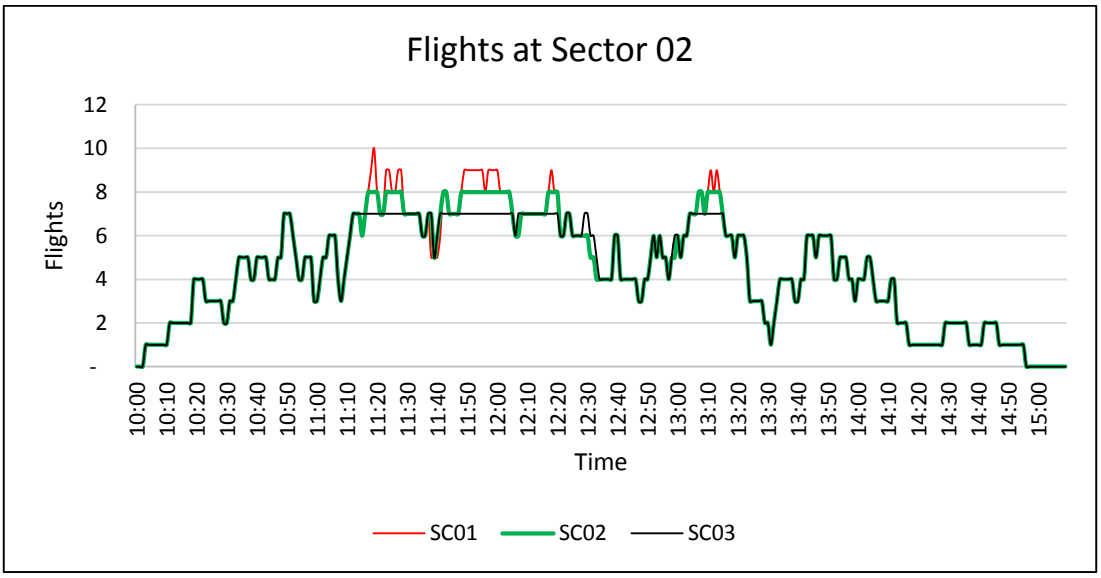



**Figure 5: Movements of flight through Sector 2 for the three studied scenarios.**

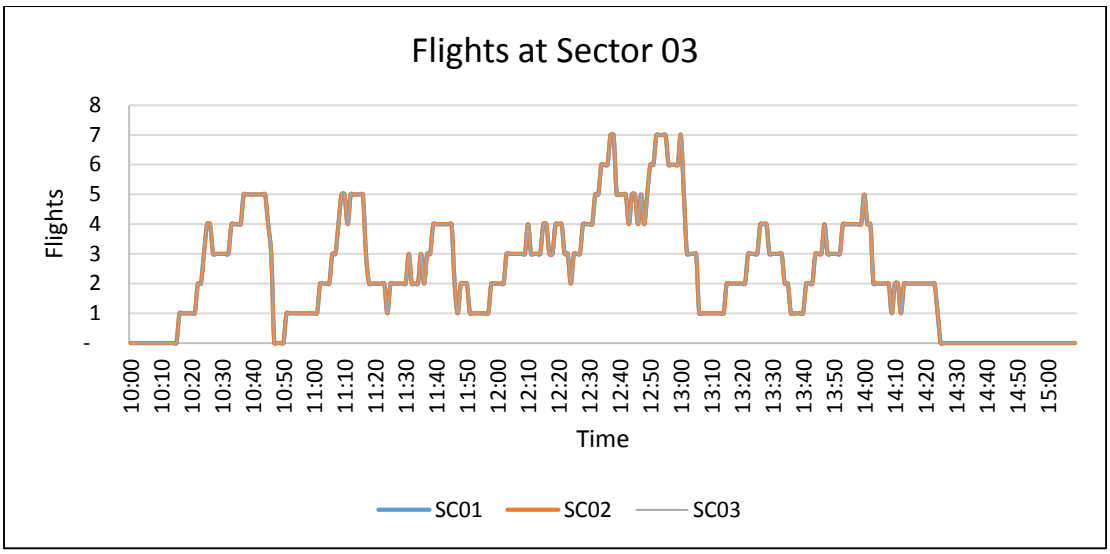



**Figure 6: Movements of flight through Sector 3 for the three studied scenarios.**

## 5. FINAL COMMENTS

This paper shows the influence of en-route weather formations on the air traffic operation and on airports. It show the impacts that three different levels of constrained sectors will have on the need to issue flow-control actions during different phases of flight. The study was able to quantify the impacts caused by these adverse weather conditions and to show how their impacts differ depending on the constrained condition presented.

The metric used to quantify the impacts are the number of ATFM actions obtained, using a dynamic optimization approach, for each one of the proposed scenario. It was possible to observe that degraded meteorological conditions have a great impact on the number of number of necessary actions to be taken, increasing in some cases, by 4 times the number of necessary ATFM action.

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