ANALYSIS OF CRITERIA FOR CLOSELY-SPACED PARALLEL RUNWAY APPROACHES: THE POTENTIAL APPLICATION OF PRM/SOIA IN SÃO PAULO INTERNATIONAL AIRPORT

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ABSTRACT

In order to increase arrival rates at many of today's heavily congested airports, simultaneous approaches are conducted on parallel runways. For many years, the FAA has recommended simultaneous independent instrument approach operations only for those parallel runways with a minimum distance of 4300 feet. Nowadays, new criteria have been developed to increase the use of parallel runways, one of these procedures, called PRM/SOIA (Precision Runway Monitor/Simultaneous Offset Instrument Approach), make simultaneous approaches possible in systems of runways spaced as close as 750 feet.

On October 26, 2004, San Francisco International Airport (SFO) implemented a PRM/SOIA landing system reportedly allowing the airport to increase the capacity of runways in inclement weather conditions up to twenty-five percent. This research, using a computer simulation tool, analyzes simultaneous approaches procedures in closely-spaced runways, addressing the potential benefits of the implementation of PRM/SOIA at São Paulo/Guarulhos International Airport (GRU) along with the influence at other airports inside the same terminal airspace (São Paulo Terminal Area – TMA-SP).

Simulation results indicate that 45 to 51% decreases in total airborne flight delays associated with flights under instrumental rules (IFR) can be achieved at the TMA-SP with PRM-SOIA usage at GRU. We also achieved an 18% increase in the arrivals capacity of TMA-SP. However, the simulation results also show increases in delays both in the departure procedures (ground queue at a specific airport) and in the airborne approaches of flights bounded to a specific airport at TMA-SP.

(RAMS Plus and ATM Analyzer utilization in this study is in accordance with the Academic Software License Agreement granted by ISA Software Ltd. to ITA).

INTRODUCTION

The increasing demand for air transportation services over recent decades has generated peaks of very high utilization of airport facilities and airspace, creating heavy congestion as the level of demand reaches a point above system capacity. As a result, many undesirable delays arise in all parts of the system, producing elevated costs for airport operators, such as air carriers and administrators. In some cases, the peak hours are further extended by other factors, such as bad meteorological conditions, which require specific procedures (instrument flight rules), increasing the distance between the flying aircraft.

In order to enhance airport airside capacity, many airports have implemented multiple runways, prioritizing the construction of parallel ones to allow simultaneous use at times of high demand. Currently, at many of today's heavily congested airports, simultaneous approaches are conducted to parallel runways in order to increase arrival rates, even under instrument flight rules (FAA, 2003 [5]).

To assure safety in such operations, restrictions have been created to guide the conducting of those simultaneous approaches, particularly in view of some factors like the spread of wake turbulence and the possibility of crashes during the approaches. As a result, in simultaneous approaches, a minimum space between runway centerlines must exist to avoid accidents like collisions or catastrophes when wake turbulence from an aircraft reaches another one.

For many years, the FAA has permitted simultaneous independent approach operations for those parallel runways with a minimum separation of 4300 feet (FAA, 2003 [5]), for instrument procedures. These operations are formed by two aircraft simultaneously doing the standard Instrument Landing System (ILS) procedure that uses standard displays: standard analog and digital Automated Radar Terminal System (ARTS) green displays (MASSIMINI, 2006 [18]).

Some airports, however, have the additional problem of limited physical space, making it impossible to construct parallel runways with the minimum prescribed distance of 4300 feet between centerlines. In some cases, the use of the marginal area is impractical due to reasons such as violations in the obstacle limitation surfaces, affecting the navigable airspace and preventing expansion of the airport.

Hence, some airports have parallel runways with reduced separations (from 4300 feet to as close as 750 feet apart) that only allow simultaneous approaches under Visual Meteorological Conditions (VMC), following Visual Flight Rules (VFR) that impose less restrictions than the Instrument Flight Rules (IFR). For those airports, the aircraft on approach need a longitudinal distance of at least five nautical miles between each other (under IFR conditions), thus restricting the approaches to only one at a time which decreases the arrival rates by approximately half.

In recent years, the FAA has approved simultaneous approaches for runways separated by at least 3000 feet. These approaches, called Precision Runway Monitor (PRM), can increase the capacity of some airports with restrictions in a physical area using a special procedure that incorporates a high update rate precision runway monitor radar system (with a 1-second update rate) rather than the standard one (with a 4.8-second update rate). Special charts and a specific communication system are also required.

There are some special cases of airports with runways separated by less than 3000 feet, not allowing the execution of the PRM approaches. One example is the San Francisco International Airport (SFO), which accepts between 60 and 65 aircraft per hour when using both parallel runways during good weather. With overcast skies, however, only one of the runways can be used because the parallel runways are separated by only 750 feet centerline to centerline instead of the 4300 feet required for side-by-side approach under Instrument Meteorological Conditions (IMC). As a result, arrival rates drop to 30 aircraft per hour. This can cause major disruptions to flight schedules, affecting passengers not only in the San Francisco region, but throughout the United States and overseas (FLYSFO, 2003 [7]).

To increase even further the utilization of those runways spaced less than 3000 feet apart, the FAA has developed Precision Runway Monitor/Simultaneous Offset Instrument Approach (PRM/SOIA) criteria, allowing simultaneous approaches to runways separated by less than 3000 feet, being as close as 750 feet apart (FAA, 2003 [5]) using two different approaches, simultaneously. One aircraft approaches a runway using the Instrument Landing System/Precision Runway Monitor (ILS/PRM), which is similar to the standard Instrument Landing System (ILS) already mentioned, but with the special equipment and procedures such as the PRM approaches. The other aircraft approaching the second runway uses a Localizer Type Directional Aid/Precision Runway Monitor (LDA/PRM) approach, which has two main differences from the ILS/PRM procedure: a 2.5 to 3.0-degree offset localizer-type directional aid (from the ILS localizer interception until the courses are 3000 ft apart) and a visual segment in the last part of the approach.

The PRM/SOIA project, a $20 million investment by SFO, is a cooperative effort between the Airport, United Airlines, Alaska Airlines, the Airline Pilots Association (ALPA), Federal Aviation Administration (FAA), and the National Air Traffic Controllers Association (NATCA), and has been in development for more than six years. The San Francisco International Airport implemented the system in October 2004, expecting an increase in the bad weather arrival rate by as much as twenty-five percent, accepting approximately 38 aircraft per hour during instrument conditions (FLYSFO, 2004 [8]). Except for the Precision Runway Monitor, the current ground and onboard technology is used in those approaches (JANIC, 2008 [16]).

GOALS OF THIS ARTICLE

The main goal of this article is to analyze the procedures for simultaneous approaches in closely-spaced runways, addressing the potential benefits of the implementation of PRM/SOIA at São Paulo International Airport (GRU), using a computer simulation tool (RAMS Plus), measuring the benefits of the implementation of the PRM/SOIA through comparisons between different scenarios.

This research will also show how this implementation can influence the capacity of the whole terminal airspace and its major airports.

PRM/SOIA

To increase the capacity of these runways separated by less than 4300 ft, the criteria called Precision Runway Monitor (PRM) was created in the late 1980s. The PRM procedure consists, basically, in two parallel instruments (ILS) and independent approaches using new features such as digital color displays with alerting algorithms (aural and visual alerts) that is associated with a PRM radar (MASSIMINI, 2006 [18]), which is more advanced than the standard displays. Such enhanced radar surveillance is required to provide the same level of safety as that achieved in more widely spaced runways (FAA, 2003 [5]). The PRM radar has a one-second update rate (rather than the standard radar with 4.8-second update rate) and the procedures include a position predictive software that provides controllers with nearly instantaneous aircraft dynamics with the reduced course separation. Specific procedures are required to provide controllers and pilots with the capability to react quickly to situations in an appropriate manner. This is achieved by requiring PRM - specific training (FAA, 2003 [5]).

These radars, along with the monitors and the position predictive software, are used for monitoring the area between the simultaneous ILS approaches, creating two areas: the No Transgression Zone (NTZ) and the Normal Operating Zone (NOZ). The NTZ area is a 2000-ft-wide no transgression zone placed in a position equidistant between the centerlines of the approach paths on the controller radar display, and begins at the highest glide-path intercept point and continues until one mile before the runway thresholds. The remaining area between the NTZ and the course centerline is the Normal Operating Zone (NOZ) (see Figure 1). Note that the size of the NTZ remains constant regardless of the runway spacing. Therefore, the size of the NOZ is reduced at closer runway spacing. A radar controller with communications override and a discrete radio frequency is required to monitor each approach path. This controller is in addition to the normal radar and tower controller required for each runway (MASSIMINI, 2006 [18]).

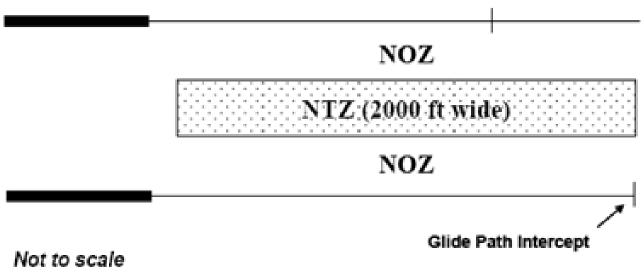


Figure 1: NTZ and NOZ.
Source: adapted from MASSIMINI, 2006 [18] .

Each final approach course is monitored by a separate controller who observes the approaching aircraft on his PRM radar monitor. If a monitor controller observes an aircraft deviating toward the NTZ, he will immediately issue instructions in an attempt to return the aircraft to the approach course. If the aircraft remains off course and enters the NTZ, a controller will immediately issue a breakout instruction to an aircraft on the adjacent final. Breakout instructions normally consist of a turn and climb or descent, avoiding collisions. Instances where aircraft actually penetrate the NTZ are very rare; however, when the monitor controller does give a breakout instruction in the form of a traffic alert, the pilot must assume that a conflict exists and ATC acts immediately. A breakout maneuver is not a missed approach or rejected landing and should be treated with the same pilot response as any other high-priority time-critical maneuver, and pilots should be prepared to respond to a breakout instruction at any time during the approach (FAA, 2003 [5]).

In addition, a dedicated monitor frequency (a secondary radio frequency) for each PRM approach is depicted. Pilots are reminded that this is a receive-only frequency, a reminder of the dual communications requirement is displayed on the approach chart. The pilot is provided with specific communications procedures that have been established to ensure that the monitor controller's transmissions are not blocked. The tower controller's transmissions are simulcast (simultaneous transmissions) on both the tower frequency and a second monitor frequency. As customary, the pilot transmits and receives on the tower frequency but, when conducting PRM approaches, also maintains a listening watch on the secondary monitor frequency. Even if the tower frequency is blocked, the monitor controller can be heard on the secondary frequency (FAA, 2003 [5]).

The Precision Runway Monitor (PRM) allows simultaneous instrument and independent approaches to parallel runways separated by at least 3000 ft, just like the standard instrument and independent approaches, and requires a 1000-ft vertical separation as far as established on the appropriate approach path and the use of normally-functioning straight-in ILS or Microwave Landing System (MLS) approaches (MASSIMINI, 2006 [18]).

Currently, many airports work with these procedures, examples in US are the Hartsfield Atlanta International Airport (ATL), and the Lambert-St Louis International Airport (STL).

In the previous section, only independent procedures were discussed, which do not depend on the longitudinal distance between the aircraft in the simultaneous approaches. Dependent approaches allow aircraft to approach parallel runways, but in instrument approaches, controllers must ensure a minimum separation from the aircraft on the adjacent approach path (diagonal spacing), in addition to maintain standard separation behind the aircraft on the same approach path (in-trail spacing). Aircraft may not overtake or be overtaken once they are established on their approaches. Table 1 provides a summary of the standards for dependent approaches (for instrument procedures), which are contained in FAA Order 7110.65R, paragraph 5-9-6 (FAA, 2006b [6]). These procedures require a 1000-ft vertical separation as far as established on the appropriate approach path, straight-in ILS or MLS, and a radar controller, but neither NTZ nor NOZ is required. Similarly, individual controllers are not required for each runway, nor are discrete communications frequencies required for each runway (MASSIMINI, 2006 [18]). For visual approaches, a minimum distance of 750 ft is required for simultaneous approaches, and it is the pilots' responsibility to maintain the aircraft at a distance from each other (although there is not a pre-determined distance), as described in the previous sections of this research.

Table 1: Dependent Approach Standards

# Runways	Radar/Update Rate (seconds)	Type Display	Min. Runway Separation (ft)	Remarks
2	Standard/4.8	Standard	2500–4300	1.5 mile diagonal
2	Standard/4.8	Standard	4301–9000	2.0 mile diagonal

Source: FAA, 2006b [6] .

At airports where the space between parallel runway centerlines is quite small, the PRM and its dependent procedures cannot be applied. Therefore, new criteria have recently been created that use similar procedures to the PRM with dependent approaches which need a certain longitudinal space between aircraft in the last part of the approaches, called Precision Runway Monitor/Simultaneous Offset Instrument Approach (PRM/SOIA).

Before the implementation of PRM/SOIA, under fair-weather conditions, San Francisco International Airport, using Runways 28L and 28R, could normally accept approximately 60 aircraft per hour. When visibility decreased due to low clouds and fog, FAA aircraft separation requirements restrict arrivals to only one runway, therefore cutting the arrival rate in half. With the PRM/SOIA in operation, inclement weather arrivals at SFO were expected to be increased by as much as twenty-five percent to approximately 38 aircraft per hour (FLYSFO, 2004 [8]).

THE CASE-STUDY: GRU

Opened in 1985, São Paulo/Guarulhos International Airport (GRU) was originally designed with the main objective of handling São Paulo’s metropolitan area’s demand for domestic flights (INFRAERO, 2000 [12]). That is to say, it was originally designed to serve medium and long haul domestic flights as well as international flights in American South Cone (MÜLLER AND SANTANA, 2008 [19]). Over the years ad hoc arrangements have been made to cope with unplanned demands.

As a result, nowadays GRU airport is the busiest airport in South America, and its terminal registered a total movement of 20,400,304 passengers in 2008. On top of that, a total air cargo weight of 425,884,098 kilograms was handled, amounting to 194,184 aircraft movements (arrivals and departures) in that same year (INFRAERO, 2009 [13]). The huge number of flights and destinations offered by the airport makes it one of the main hubs in Latin America, as it concentrates several connections between South American countries. Therefore, most passengers coming from Europe and the United States have connections there on their way to other Brazilian cities and countries in South America (MARQUEZ, 2006 [17]).

The airport complex now operates at the limit of its capacity. In 2007, 18.7 million passengers went through the airport gates, an increase of 19.27% when compared with the flow of passengers of the previous year. In December of that year alone, more than 1.8

million people used the airport terminal, an increase of 31.59% when compared with the statistics for the same month of the previous year (INFRAERO, 2009 [13]). Despite such high growth rates, the construction of the new terminal (the third passenger terminal) has not yet started. The administration of the airport (*Empresa Brasileira de Infraestrutura Aeroportuária* - INFRAERO) expects a capacity increase from 17 to 29 million passengers a year in the passenger terminals (landside capacity) with that new building (INFRAERO, 2009 [13]).

However, the main project designed to increase the airside capacity, the construction of the third runway, is currently almost abandoned. Because of problems related to the limited physical space (due to the fact that the airport is totally inserted in the urban area), this project proposes a short new runway (when compared with the current runways) of between 5905 and 6643 ft in length (separated by 4796 ft from the runway 09L/27R) used mainly for arrivals. Despite the small size and the restrictions on use, studies (SANTANA, 2002 [23]) have clearly measured the impact of a third runway in reducing delays (in both arrivals and departure operations) and decreasing operational problems at the airport. Probably, the decision to halt the project is related to physical restrictions, like the violations in the slopes of aeronautical planning (legislation on the aerodrome's flight path protection areas), due to urban constructions (such as buildings and antennas) that have been developed in recent years. Currently, the slopes of the aeronautical planning have already been violated by a list of existing obstacles such as a set of trees, radio-taxi antennas, a gas station, church tower, buildings and others, making it difficult even to expand the current runways.

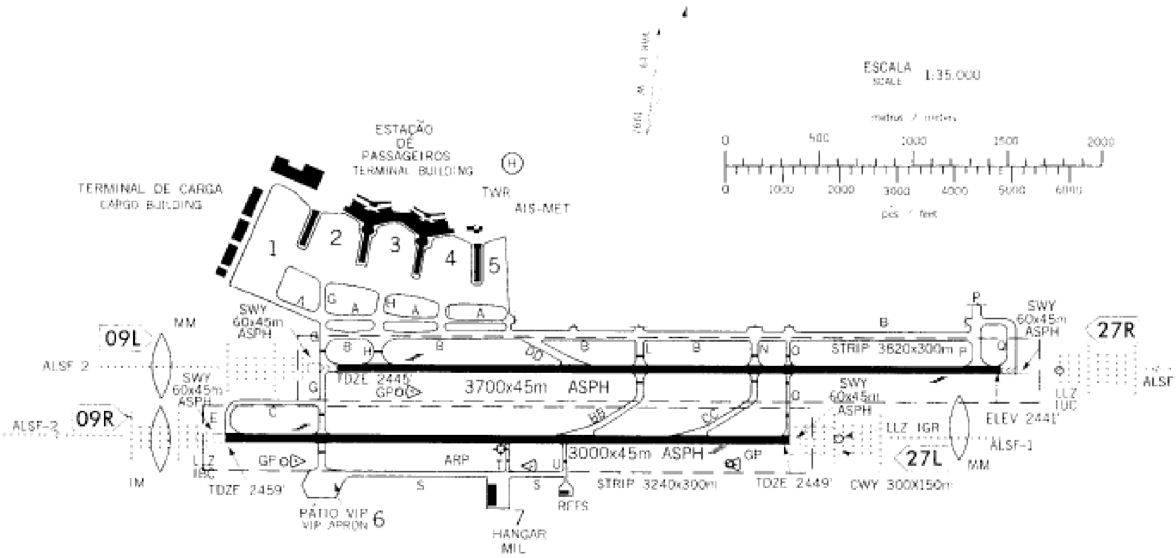


Figure 2: Current scheme of São Paulo/Guarulhos International Airport (GRU).
Source: adapted from AISWEB, 2009 [1] .

METHODOLOGY

This section shows the methodology used to construct the different scenarios for measuring the potential benefits of the implementation of PRM/SOIA in São Paulo/Guarulhos International Airport (GRU), using the RAMS Plus simulator: a ATC/ATM fast-time simulator tool, which operates in the simulation of airside area.

All the material used will be presented here (such as the many types of aeronautical documents and charts) in the models, the real data bank applied in the simulations, the instruments used for the validation of the scenarios and some limitations found in the construction of the models in RAMS Plus. These benefits of using SOIA at GRU were measured through a comparison between such scenarios: current procedures versus new procedures. Such comparisons will be shown in the results section.

SIMULATION TOOL

In this research, the Reorganized ATC Mathematical Simulator (RAMS Plus) tool (version 5.29.15) was used to analyze the advantages of the implementation of the PRM/SOIA procedures at GRU. This software is a gate-to-gate ATC/ATM fast-time simulator tool, which helps answer a spectrum of questions about the ATM system, from airspace design, capacity, working procedures, safety concerns, to airport movements, capacity and delay (ISA SOFTWARE, 2003 [14]), as used in lots of studies about runway system and airspace capacity.

SCENARIOS: MODELING CURRENT AND PRM/SOIA PROCEDURES

Visual procedures are now being replaced by instrument procedures (OLMOS AND MUNDRA, 1999 [20]) for many reasons, such as the increase in safety during IFR procedures in comparison with VFR procedures. GRU does not have visual procedures, even under Visual Meteorological Conditions (VMC). Therefore, the scenarios were created using all the current instrument procedures at the São Paulo Terminal Area (TMA-SP). These include all the airports in the TMA-SP which have instrument procedures: São Paulo/Guarulhos International Airport (GRU), São Paulo/Congonhas Airport (CGH), and Campinas/Viracopos Airport (VCP). Therefore, the scenarios have been modeled using the Standard Instrument Departure (SID) and the Standard Terminal Arrival Route (STAR) charts for the three airports (see Figure 3).

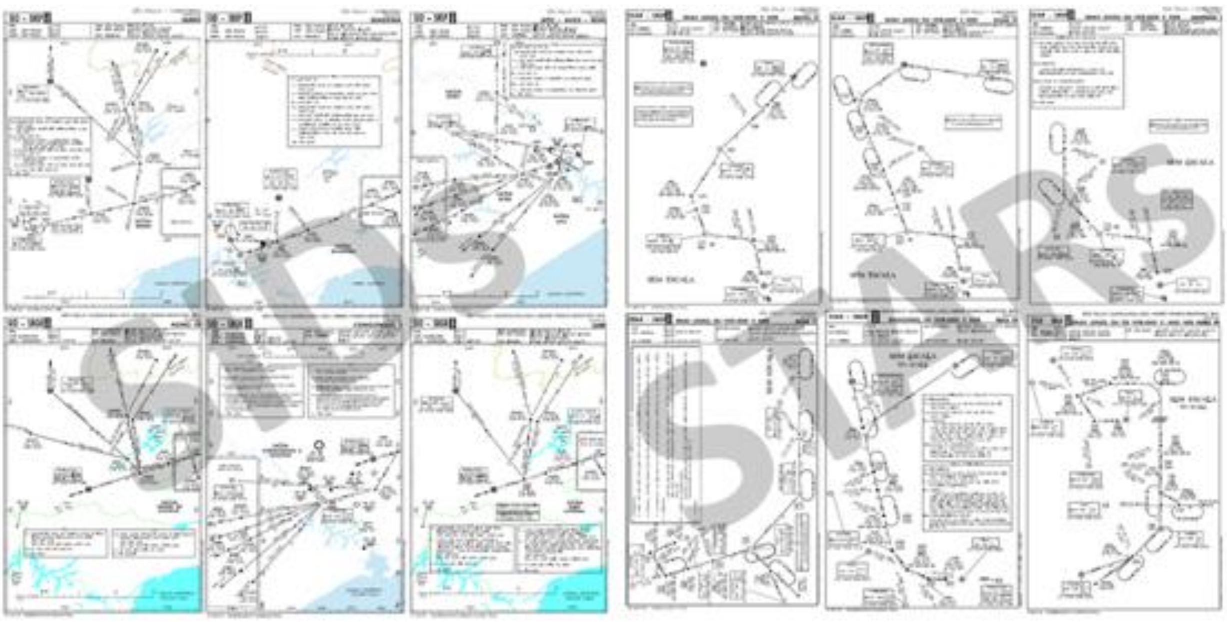


Figure 3: Some SID and STAR charts.
Source: adapted from AISWEB, 2009 [1] .

In order to devise the new procedures (PRM/SOIA scenarios) we decided to closely emulate the procedure already established at San Francisco International Airport (SFO), but taking into account the features of the TMA-SP, such as mountains and elevation of the runways, and using the thresholds with the highest utilization rate: 09 for GRU, 17 for CGH and 15 for VCP. Hence, we used the PRM/SOIA charts from SFO to create the PRM/SOIA geometry for GRU. Figure 4 shows the geometry of the PRM/SOIA procedures created for GRU in one of the segments (the last segment), where the LDA PRM approaches are conducted in the 09R threshold, and the ILS PRM approaches are conducted in the 09L threshold. All the segments were modeled with the help of AutoCAD so as to achieve a high level of precision in the construction of each segment (construction of way points, routes, angles, distance between paths and other factors that required extreme precision), to be imported into the RAMS Plus simulator.

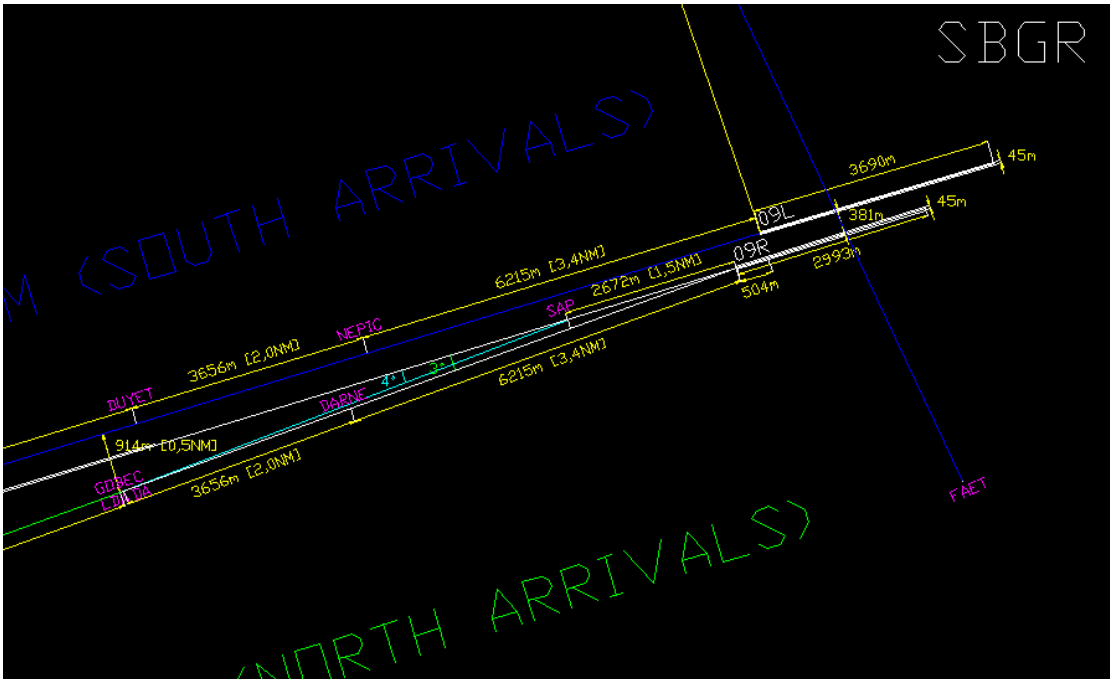


Figure 4: Last segment of the approaches modeled in AutoCAD software.

We have two different scenarios, a scenario modeling the current procedures and another modeling PRM/SOIA procedures:

- Scenario 1: simulation of the current procedures in the TMA-SP.
- Scenario 2: PRM/SOIA simulation at GRU and current procedures in the other two airports modeled (CGH and VCP).

We followed the ICAO rules to construct these procedures (ICAO, 1999 [9] ; ICAO, 2006 [10] ; ICAO, 2007 [11]), considering a RNAV system that uses satellite technology, requiring a semi-width of 2.5 nm. Therefore, for these approach segments, the separation between the approaches needs to be at least 5 nm, as shown in those rules (ICAO, 1999 [9] ; ICAO, 2006[10] ; ICAO, 2007 [11]). Figure 5 shows these separations and the soft angles of the constructed routes.

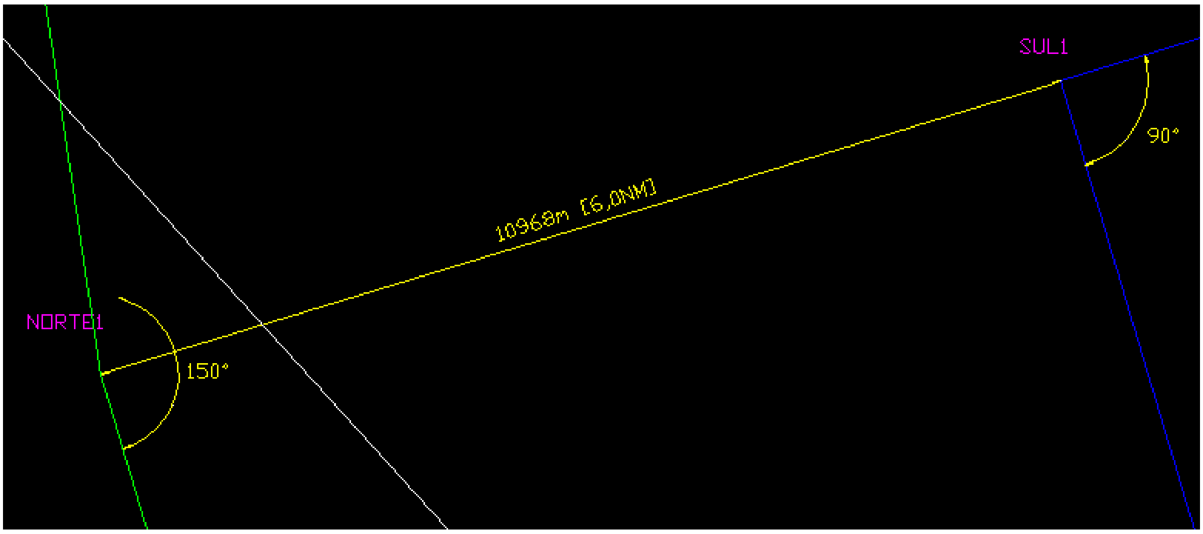


Figure 5: Separations between STAR for CGH and GRU, with the angles of the turns.

With regards to the missed approach maneuvers, we considered the mountains to the northeast of GRU, proposing that the two simultaneous approaches can execute simultaneous missed approach maneuvers with one of them following a straight direction (09L) and the other turning to the right (09R). Besides, due to the high utilization rate of the 09 thresholds, we modeled only these procedures, disregarding the approaches for the 27 threshold. Hence, we also disregarded the aprons of the airport in the construction of the scenarios, due to the fact that easy expansion of these facilities is possible as new aprons can be constructed in the northeast area (the planned aprons of the 3rd and 4th passenger terminals). Some airports now decide to construct the aprons before their terminal, decreasing apron congestion.

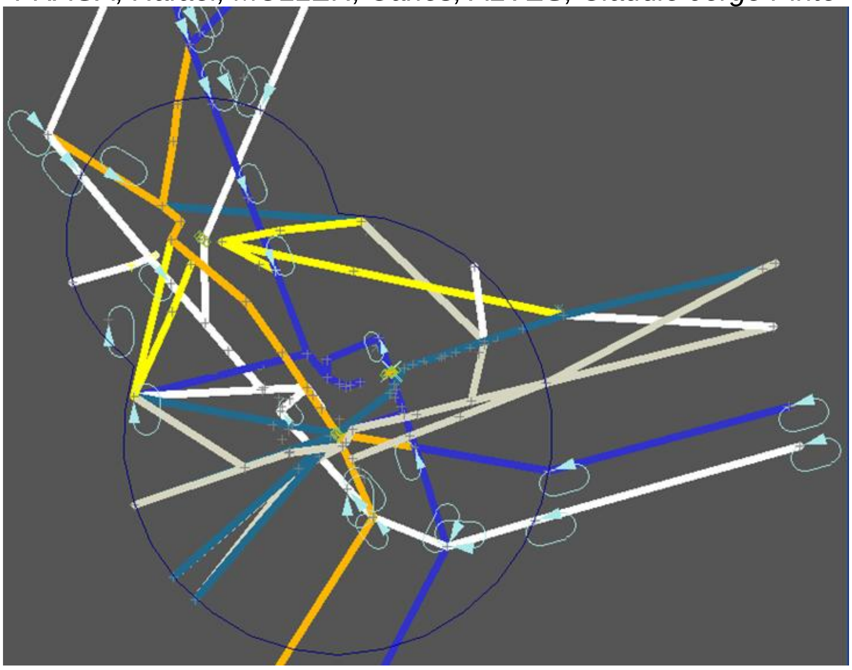


Figure 6: TMA-SP: current IFR procedures modeled in RAMS Plus.

ASSUMPTIONS AND LIMITATIONS

In order to achieve the goals of this article, it is extremely important to share the assumptions in all of the models. One of the most important considerations was the vertical separation established between GRU and CGH final approaches in the PRM/SOIA scenario (scenario 2), trying to reduce the relationship between the approaches for both airports. We decided to adopt this procedure following previous studies (generated by the Brazilian airspace authority) trying to measure the benefits of the implementation of PRM/SOIA criteria at GRU, since these studies disregard the vertical separation, producing significant capacity losses at CGH that make this implementation not feasible. In addition, other assumptions were made:

- Regarding the fact that there is sufficient area to construct new aprons at GRU, we did not model ground operations at the aprons, since these constructions can completely modify the simulated operations.

- In order to validate the PRM/SOIA scenario, we copied the approach patch of SFO in an exact way and applied it to GRU, regarding specificities at TMA-SP (such as the different runway elevations between GRU and SFO).

- The scenarios were constructed with the approach routes related to the runway thresholds with the highest utilization rate, i. e. thresholds 09L/R for GRU (80% utilization rate), thresholds 17L/R for CGH (70% utilization rate), and threshold 15 for VCP (89% utilization rate). These utilization rates were collected along an entire year (from February 2008 to January 2009), using the SGTC data bank (Control Tower Management System).

- As CGH runway 17L/35R only operates some rare extra movements (general aviation), we ignored this runway directing all the traffic to the longest runway (17R/35L).

Regarding the fact that both scenarios ignore such runway, the results coming from the comparison of both scenarios will control this non-observed fact. We consider that this controlled non-observed phenomenon at CGH will not influence the results about the benefits of the implementation of PRM/SOIA at GRU.

We found some problems in RAMS Plus in constructing the PRM/SOIA approaches, due to some limitations and incompatibility of the software for modeling these procedures. One of the most problematic limitations is that the current version of the software is unable to set a reduced separation just for a pair of aircraft in a specific segment, creating reduced separations during the whole terminal area between a series of aircraft.

To solve these problems we divided the approaches into two groups: STAR from the south and STAR from the north and west, allowing reduced space only at the intersection point between these groups. As a result, the aircraft maintain a conventional (standard) separation during the whole procedure, only reducing the separation between aircraft of different groups, and this reduction only happens if at the intersection point the separation between these two aircraft is smaller than 5 nm. In this case, both aircraft will adjust their approach speed to make closely-space approaches, executing a PRM/SOIA procedure, as shown in Figure 7.

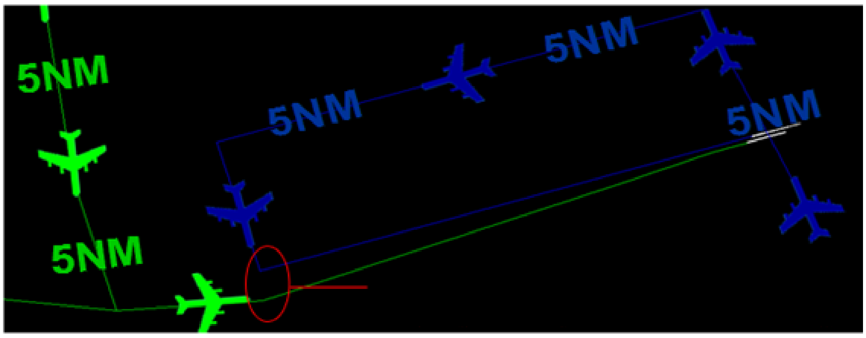


Figure 7: Intersection point between STAR from the south and STAR from the north/west:.

However, this configuration can also underestimate the benefits derived from the PRM/SOIA procedure, due to the impossibility to conduct PRM/SOIA procedures by aircraft with the same origin point. In addition, another problem is with regard to the determination of the leading and the trailing aircraft: the software does not support reduced separations between a specific trailing/leading aircraft, as established in the manual: “when using this 5th optional field, the order of following and leading SID/STAR is not relevant, instead the SID/STAR combination is treated in any order” (ISA SOFTWARE, 2006 [15]). As a result, sometimes the leading and the trailing aircraft execute the PRM/SOIA procedures in changed positions where, regarding the PRM/SOIA concept, the trailing aircraft must execute the LDA/PRM approach and the leading aircraft must execute the ILS/PRM approach.

THE DATA BANK

The data bank comprises the IFR traffic of the three airports at TMA-SP, on a typical day: 03/06/2008, with 1030 traffic events. The scenarios were created using all the current IFR procedures at the São Paulo Terminal Area (TMA-SP), so these include all the airports in the

TMA-SP with IFR procedures: GRU, CGH and VCP. This typical day faithfully represents the annual demand for this airport as can be seen on Table 2 that shows a comparison between the annual average delay and the average delay on the typical day, for all TMA-SP traffic. As annual statistics could contain some outliers, increasing the average, we considered only delays of a maximum of 1 hour, trying to count only the typical delays.

Table 2: Comparison between average delays for all TMA-SP traffic

Annual (min)	**Typical day (min)**	**Difference (% of the annual average)**
11.23	11.72	4,3%

In a comparison between the annual mix of aircraft and the mix of the typical day, these four mixes analyzed (GRU, CGH, VCP and entire TMA-SP) are very similar in both tables, with mix index in the same category according to FAA runway capacity method (the Advisory Circular No 150/5060-5), as showed in the tables below.

Table 3: The annual mix of aircraft (from Feb 2008 to Jan 2009), using SGTC data bank

Airport	**CAT A/B**	**CAT C**	**CAT D**	**Mix Index (C + 3D)**
GRU	7.9%	69.8%	22.3%	137
CGH	9.2%	90.8%	0.0%	91
VCP	19.5%	63.0%	17.5%	115
Entire TMA-SP traffic	9.4%	78.2%	12.3%	115

Table 4: Mix of aircraft on the typical day chosen (06/03/2008)

Airport	**CAT A/B**	**CAT C**	**CAT D**	**Mix Index (C + 3D)**
GRU	9.6%	69.1%	21.3%	133
CGH	8.9%	91.1%	0.0%	91
VCP	13.4%	76.3%	10.3%	107
Entire TMA-SP traffic	9.7%	78.2%	12.1%	115

Table 5: Mix Index categories - Advisory Circular No 150/5060-5

Mix Index (C + 3D)
0 to 20
21 to 50
51 to 80
81 to 120
121 to 180

Source: FAA, 1983.

Even comparing the annual averages with a typical day, the typical day had 1030 IFR events (in the entire TMA-SP), a very similar value compared to the annual average (for IFR traffic) in this area: an average of 1055 aircraft from Feb 2008 to Jan 2009, also using SGTC data bank (Control Tower Management System) and disregarding the helicopter operations.

Finally, the most used thresholds on these three airports were operating on the typical day (GRU 09L/R, CGH 17L/R and VCP 15).

VERIFICATION AND VALIDATION

Jain (1991) [16] defined both validation and verification (BASTOS, 2009 [3]):

- Verification: Actions in order to assure that the simulation model is consistent with the real situation.
- Validation: Procedures to assure that the result of the models are consistent with the reality.

Balci (1995) [2] presented some validation, verification and testing techniques. Regarding to Balci's diagram, the following activities had been done in order to verification and validation of both scenarios:

- Informal inspections and dynamic visualization: the models were analyzed by air traffic control specialists with long experience in the TMA-SP and RAMS Plus software, i. e. informal inspections and dynamic visualization of the models involving airspace design, aircraft performance (flight path, speed, altitude etc), and others. These procedures are more closely related to the current scenario (scenario 1). More specific to the PRM/SOIA scenario (scenario 2), as already explained in the previous sections, we decided to project the new PRM/SOIA approaches using the exact approach path working at SFO, avoiding validation problems with this scenario since the only construction differences between scenario 1 and 2 are the final segment of the approaches for GRU (PRM/SOIA approaches). Balci (1995) [2] , Rao (1998) [22] and Phillips (2000) [21] pointed problems in validation of future scenarios, since there is no way to compare with the reality (BASTOS, 2009 [3]).
- Graphical Comparisons: comparisons with another RAMS Plus model, related with the current procedures in TMA-SP – BAUM (2009) [4] .
- Stress testing: creation of exaggerated artificial demand, in order to achieve the ultimate capacity of the model (third stage of results section) and also using to validate scenarios. In this second proposal, we used this stress modeling in order to identify problems in the models caused by high demand level.
- Statistical techniques: a comparison was elaborated between the real daily distribution delay (on the typical day chosen) obtained through real statistics called SGTC data bank (Control Tower Management System) and the daily distribution delay recorded in the simulation of this typical day (scenario 1), both for traffic in TMA-SP, showing very similar values.

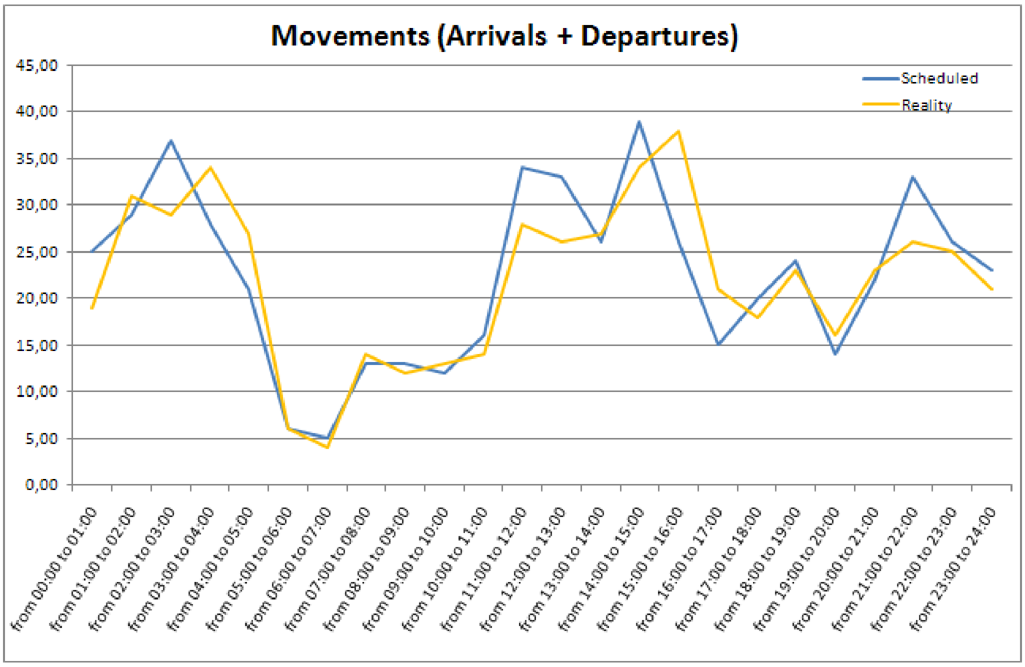
Another validation comparison can be made using the real hourly movements and the simulated hourly movements. There are comparisons in table 6 for each airport between the numbers of movements in the peak hours, the average number of movements between the five peak hours (top 5 above average) and the average number of movements between the five lowest-traffic hours (top 5 below average). The "difference" column displays the difference between the real and simulated values, in a percentage from the real values, where it is easy to observe the resemblance between real and simulated values. These analyses were made using the replication with best statistical significance.

Table 6: Comparison between real and simulated average daily delay for all TMA-SP traffic

Airport	Value analyzed	Real	Simulated	Difference
GRU	Peak	37	34	8%
	Top 5 above Average	32.8	32.2	2%
	Top 5 below Average	9.4	9.6	2%
CGH	Peak	33	38	15%
	Top 5 above Average	29.8	34.8	17%
	Top 5 below Average	0	0	0%
VCP	Peak	10	10	0%
	Top 5 above Average	8.4	7.4	12%
	Top 5 below Average	0.2	0.2	0%

Finally, the Graph 1 shows the differences between the hourly movements in the real statistics and simulation outputs, at GRU airport. There are some differences, but the major share of the curves follows the same directions.

Graph 1: Differences between real and simulated hourly movements at GRU airport



As the original data bank (the SGTC data bank) utilized to construct the data bank files inserted in the simulator does not contain the times at which the aircraft entered in the terminal airspace boundaries, we had to calculate these times using the landing times for each flight. For this, we estimated the duration of the flights from terminal airspace entrance points to the airports. As a result, naturally, the small differences discovered in tables and graph above represent this process.

RESULTS

In the first stage of the research, we simulated the scenarios using a data bank of only one day: 03/06/2008, a typical day, with 1030 movements in the TMA-SP for the three airports analyzed (arrivals and departures). At this point, related with the stochastic tasks, each scenario was simulated 10 times, and the stochastic tasks are: aircraft performance, runway occupancy, task weight, controller window, airport taxi. These tasks varies in a normal distribution with mean = 1 and standard deviation = 0.03; this is, basically, varying from approximately 90 to 110% of the normal condition. This variation of 10% above or below the perfect conditions (between 90 and 110%) was an assumption of the modeling process.

In the second stage, we added stochastic tasks related with the time that the aircraft enter the system (in the terminal area), using the same typical day, but changing these aircraft entrance-times in a random way using the standard Microsoft Excel algorithm to generate new times between 0 and 2 hours for each traffic: another assumption of the modeling process. Hence, we summed these values (between 0 and 2 hours) to the original ones, for all traffic. As a result, we obtained a new data bank simulating stochastic delays between 0 and 2 hours in all the traffic for the typical day chosen, where the delay varies for each flight.

To obtain a significant result, we did this same procedure ten times, creating ten different data banks with aircraft entering the system in different times that vary between 0 and 2 hours from the original data bank (the data bank of the typical day chosen). Thus, in the second stage, we simulated these ten data banks for each scenario, also using the stochastic tasks related with aircraft performance as in the first stage.

In this article we are going to show only the first stage results. The averages of this results (10 replications) are displayed in the following table, showing the variations (difference) in percentage for scenario 2 in comparison with scenario 1 (the baseline scenario, simulating the current procedures); where green values indicate decreases caused by the implementation of PRM/SOIA, and red values indicate increases. All the averages showed a standard deviation of less than 15% (of the average).

Table 7: Operational times from the simulations for all the aircraft

Scenarios	Total simulated airborne flight time	Total airborne flight delay	Mean airborne flight delay	Standard deviation	Total ground departure queue delay	Total airborne flight distance (NM)	Total fuel consumption

Scenario 1	27913.02	10638.15	10.32	17.15	3933.79	89757.68	1925784.15
Scenario 2	23718.26	5206.75	5.05	8.48	4443.70	94847.33	1681280.53
Difference	**15%**	**51%**	**51%**		**13%**	**6%**	**13%**

According to Table 7, the airborne delays (analyzing the entire scenarios or only the TMA-SP area) decreased by 51%, where this reduction on the holdstack time reduced the total simulated airborne flight time in 15%. This happens even with the increase in the total flight distance of 6% in the PRM/SOIA scenario (in a comparison with the current conventional approaches), due to the enlargement of approach path required in the PRM/SOIA procedures.

As a result, the average airborne delay per aircraft registered in the simulation of the current procedures is approximately 10.5 minutes, while, for the PRM/SOIA procedures, this value is around 5 minutes, analyzing the entire scenario. This happens even with the increase in the total flight distance, where the average flight distance per aircraft in scenario 1 is around 87 nm, and increased to approximately 92 nm in scenario 2.

These results presented so far are related to all the aircraft in the entire scenario. In the following paragraphs we will start to analyze the results in an isolated way for each airport.

As noticed in previous sections, we already expected that PRM/SOIA can extend the average time on the ground for the departing aircraft, increasing the queues for takeoff due to an increase in the arrivals at the airport that implemented these procedures (GRU). Hence, the results in table 7 and 10 show this increasing phenomenon.

The mean departure queue time at CGH basically did not change (table 11). This means that, with our vertical separation between crossed approaches, the PRM/SOIA implementation at GRU does not change significantly the quantity of movements for the peak-hours at CGH, for this simulated demand (the simulated day). Table 9 shows this phenomenon, where the maximum number of arrivals/hour at CGH is 23 in both scenarios, and the maximum number of departures/hour at CGH is 20 in scenario 1 and 21 in scenario 2 (that is, higher in scenario 2), but the average between the top 5 departures is almost the same for both scenarios. Finally, the number of movements/hour at CGH (that is, summing arrivals and departures) is higher in scenario 1, but the average between the top 5 departures is higher in scenario 2. As a result, we can conclude that, for this simulated demand, the implementation at GRU does not produce a significant modification in the quantity of movements in the peak-hours at CGH, once this result can show that the capacity of this system (airspace) is probably higher than this typical demand simulated.

Table 8: Maximum hour rate and average between the top 5 rates for each scenario (CGH)

Congonhas Airport (CGH)	**Arrivals**		**Departures**		**Movements (A+D)**	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Max	23	23	20	21	40	38
Top 5 Average	20.4	20	18.6	18.8	35.2	36.6

Table 9 shows the same metrics as at GRU, and, for this airport, we can observe significant differences between scenarios. The arrivals maximum rate and the top 5 arrivals average increases by 26% and 20% in scenario 2, respectively (in a comparison with scenario 1). The departure maximum rate and the top 5 departure average decreases by 4% and 2% in scenario 2, respectively (in a comparison with scenario 1). These opposite values between arrivals and departures produce the resemblance in the number of movements: the same values for maximum hour rate and top 5 departure average for both scenarios.

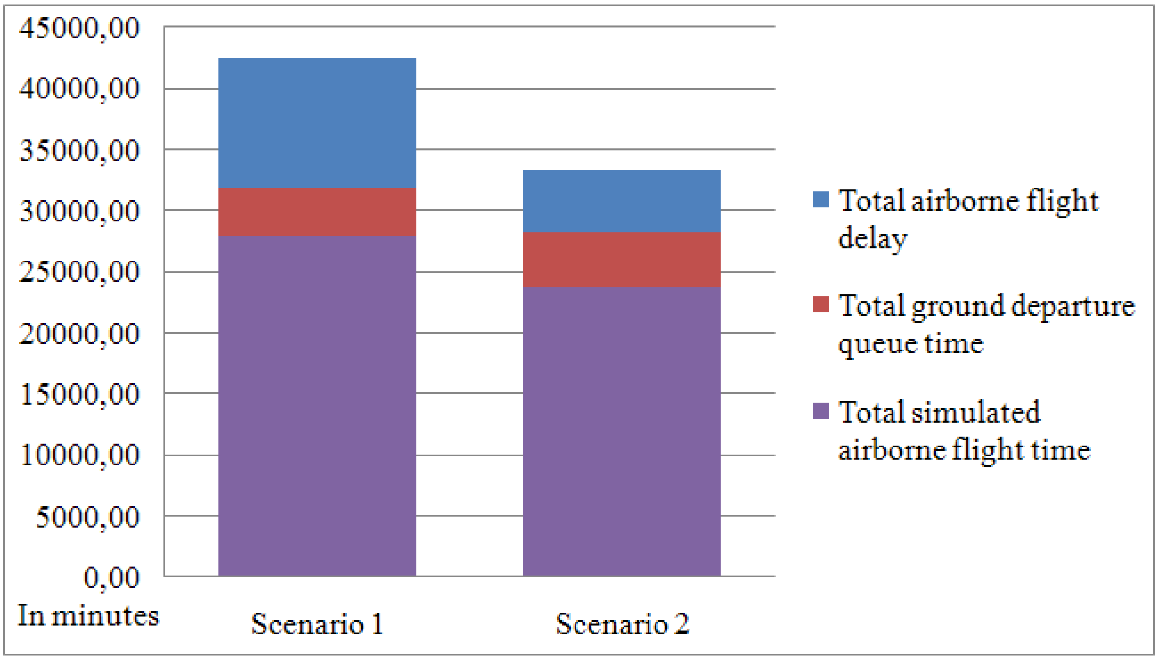
Table 9: Maximum hour rate and average between the top 5 rates for each scenario (GRU)

Sao Paulo Intl Airport (GRU)	**Arrivals**		**Departures**		**Movements (A+D)**	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Max	19	24	23	22	34	34
Top 5 Average	15.8	19	20	19.6	32.2	32.2

Since this demand cannot reach the ultimate capacity, we considered that this analysis is not significant to evaluate the ultimate hourly capacity of the system. In order to evaluate these changes in the quantity of movements, in a more significant way, in the third stage of the results analysis we will produce an artificial demand increasing the original one (typical day) to obtain the ultimate hourly capacity for these runway systems for each scenario.

Graph 2 displays the same metrics as Table 7 in a unit comparison, presenting the sum of these times in the right axes. It is easy to see the relevant differences between the scenarios PRM/SOIA (scenario 2), the baseline (scenario 1) and the large importance of the "total airborne flight delay" reduction. These results are related to all the aircraft in the entire scenario.

Graph 2: Times registered in each scenario



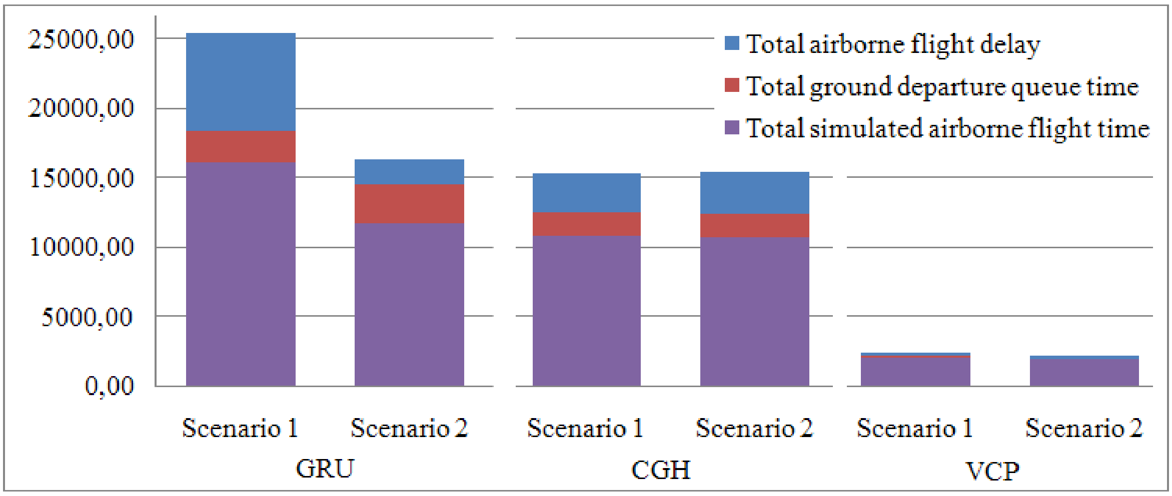
In order to evaluate how the PRM/SOIA implementation at GRU affects each one of the three modeled airports (the airports with IFR traffic in the TMA-SP), the table below shows these four metrics ("total simulated airborne flight time", "total airborne flight delay", "total ground departure queue delay" and "total airborne flight distance") in a comparison between both scenarios for each airport. The green values indicate decreases caused by the implementation of PRM/SOIA, and red values indicate increases. No significant changes were observed in the "total airborne flight distance" for CGH and VCP: this happens because any changes were produced for both metrics at these airports, since there are no changes in the route. However, at GRU airport, the routes and the operational features of runways are changed in scenario 2, increasing the flight paths.

Table 10: Operational times from the simulations for each airport

Airport	Scenarios	Total simulated airborne flight time	Total airborne flight delay	Total ground departure queue delay	Total airborne flight distance (NM)
GRU	Scenario 1	16060.01	7123.21	2275.39	46797.26
	Scenario 2	11776.55	1844.36	2732.79	51796.51
	Difference	**26%**	**74%**	**20%**	**11%**
CGH	Scenario 1	10800.27	2857.58	1651.84	37503.04
	Scenario 2	10681.43	2996.13	1704.77	37776.88
	Difference	**1%**	**5%**	**3%**	**1%**
VCP	Scenario 1	2108.04	276.66	6.56	7217.13
	Scenario 2	1972.77	214.08	5.54	7310.57
	Difference	**6%**	**23%**	**15%**	**1%**

According to Table 10, analyzing the results in an isolated way, the simulation of the implementation of PRM/SOIA at GRU reduces the total airborne flight delay by 74% at this airport. However, analyzing only the CGH traffic, the total airborne flight delay increases by 5% in scenario 2. Analyzing only the traffic at VCP, the total airborne flight delay decreases by 23% in scenario 2. Regarding "total ground departure queue delay", these averages increase for GRU and CGH airports by 20% and 3%, respectively, in scenario 2, and decrease by 15% for VCP. As an outcome, both metrics analyzed show that the implementation of PRM/SOIA at GRU generates positive impacts for VCP airport, but negative impacts for CGH airport. This may happen due to the existence of overlapping points in those approaches, creating an airspace where different approaches (for different airports) generate influences in the capacity of each other. But, graph 3 below shows that the significant change happens just at GRU.

Graph 3: Times registered in each scenario at each airport



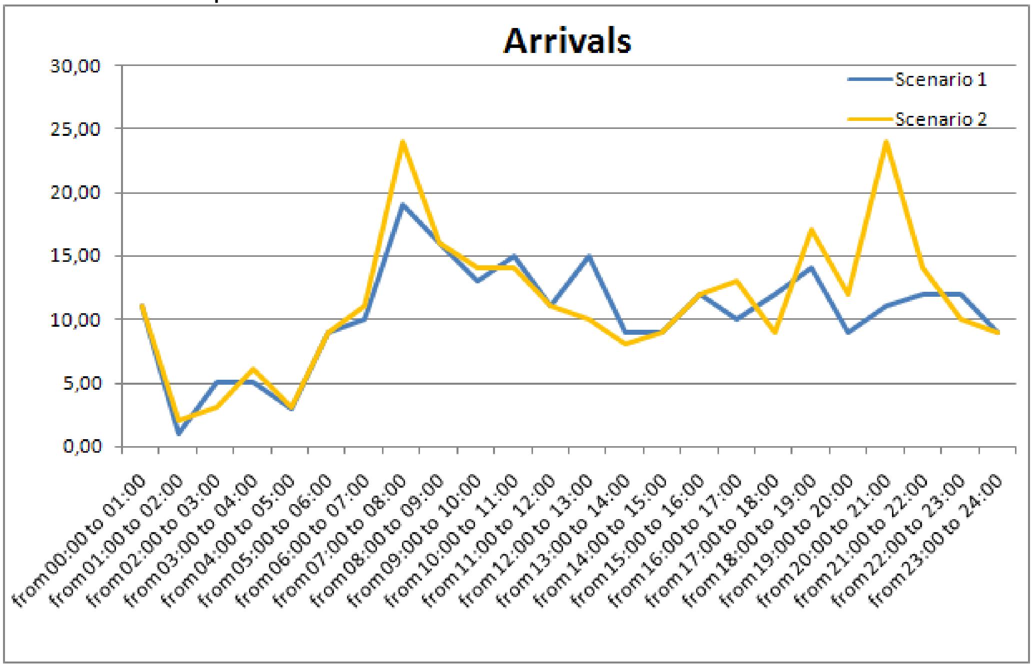
Just to confirm the actual relationship between the airports and the dependent capacity of the system (overlapping points in the airspace), we also analyzed the direct impacts of the CGH traffic (the traffic that generates more impacts for GRU capacity) in the current procedures (scenario 1). Thus, we simulated this scenario without the traffic from CGH airport. The table below shows the comparison between two simulations of scenario 1: one simulation with the original demand of the typical day chosen, and another simulation with the same data bank without the CGH's traffic. As a result we can note, removing CGH traffic, the total airborne flight delay decreases by 36%, proving the intense relationship between the traffic.

Table 11: The impacts of the CGH traffic at GRU and VCP capacity

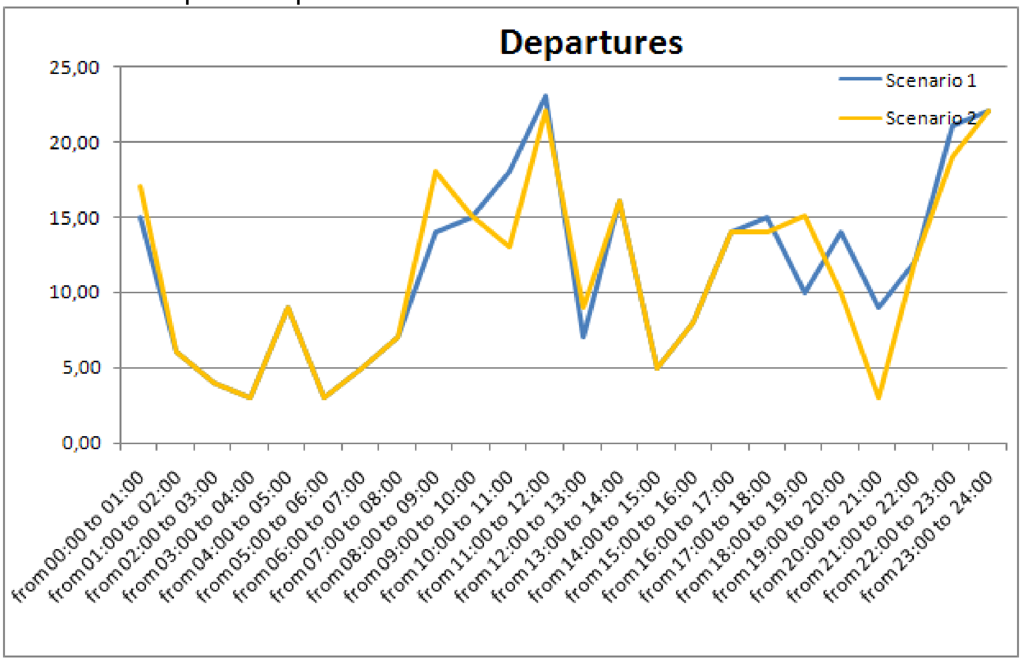
Simulation	**Total airborne flight delay at GRU and VCP**
Typical day demand with GRU, CGH and VCP	7399.86
Typical day demand with GRU and VCP (without CGH)	4770.45
Difference	**36%**

The Graphs 4, 5 and 6 (below) represent the movements/hour at GRU airport. We can observe that, in the simulation of current procedures (scenario 1), the peaks for operations/hour are lower than the peaks for operations/hour in scenario 2 for the arrivals, but higher in scenario 1 for the departures. As a result, this fact generates very similar graphs for both scenarios in the number of movements/hour (Graph 6), that is, summing arrivals and departures. This shows exactly what was explained in Table 11 above. These three graphs were made using replication with best statistical significance (the replication with lowest deviation from the mean).

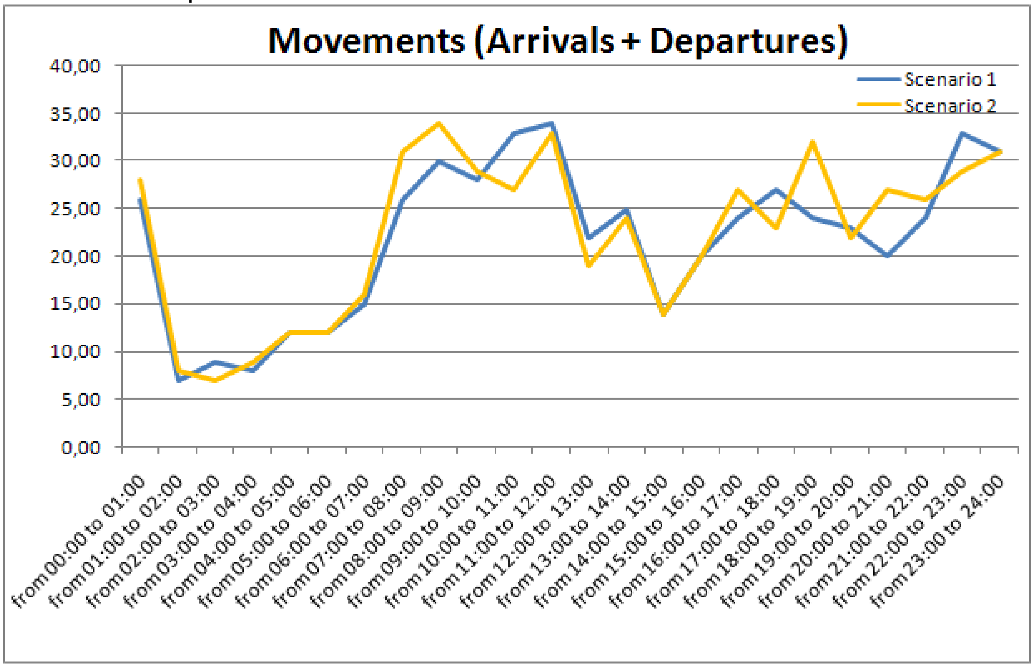
Graph 4: Arrivals/hour at GRU: Current vs. PRM/SOIA



Graph 5: Departures/hour at GRU: Current vs. PRM/SOIA



Graph 6: Movements/hour at GRU: Current vs. PRM/SOIA



CONCLUSIONS

The results of this research point to several benefits in the implementation of PRM/SOIA approaches at São Paulo/Guarulhos International Airport (GRU), such as significant reductions of airborne delays (between 45 and 51%).

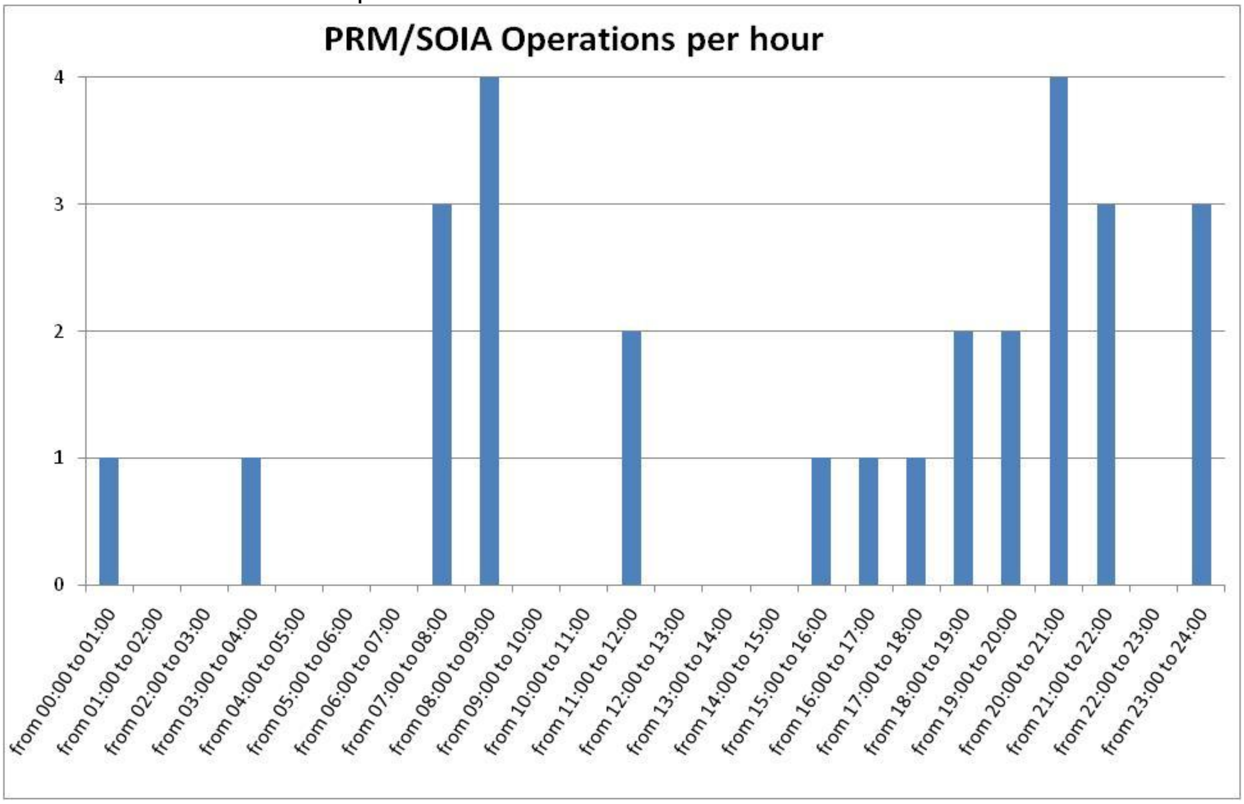
However, as expected, the average time on ground for departing aircraft increased with the implementation of the new procedure, resulting longer queues for takeoff. This happens due to an increase in the arrivals at the airport that implemented these procedures (GRU). As we already showed, due to some incompatibilities of the simulation tool on these PRM/SOIA procedures, the results can be a little overestimated.

This work also shows the close relationship between the airports in TMA-SP, pointing to the importance of treating runway capacity studies as a system, rather than isolated means. Perhaps this could be the reason for the large differences between the results showed in the simulations and in the FAA method, regarding the capacity of the runway systems.

According to this relationship, we analyzed how the implementation of PRM/SOIA approaches at GRU airport impacts the operations at the other two major airports of this terminal airspace, showing some losses at Congonhas Airport (CGH) and larger gains at Campinas Airport (VCP) in both metrics analyzed: total airborne flight delay and ground departure delay. For CGH these values increase by 5 and 3%, respectively; and for VCP these values decrease by 23 and 15%, respectively.

Finally, the last graph below shows the quantity of hourly PRM/SOIA movements in our baseline simulation (first stage simulation), for the replication with best statistical significance (the replication with lowest deviation from the mean), regarding all the simultaneous approaches separated by less than 1.2 minutes (approximately 3 nm, considering an average approach speed of 150 knots) as PRM/SOIA procedures. For this simulated day, a total of 28 pairs of PRM/SOIA approaches were conducted (56 approaches), representing 20.22% of the total of approaches (277 approaches) conducted to GRU airport in this simulation.

Graph 7: PRM/SOIA Movements/hour at GRU



Since this research seeks the potential benefits of the implementation of PRM/SOIA at GRU airport, the benefits identified in this work can motivate future efforts to measure the safety of those procedures in this terminal airspace (São Paulo Terminal Area, TMA-SP); can also motivate future research related to the financial analysis of its implementation and on its meteorological issues.

This work can be applied to any multiple airport system in the world.

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