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Efficiency analysis of a congested Brazilian airport applying slots optimization control: Congonhas Airport Case

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The quick development of air transport combined with restricted airport capacity has resulted in genuine imbalance between demand for airport services and provision of the air terminal assets needed. As a result, there is a shortage of about 200 airports around the world that are overly congested (IATA, 2017). Congestion has several undesirable effects such as cost for airports, airlines and discomfort for passengers. It occurs whenever demand exceeds capacity. In the case of airports, it has been caused because of the imbalance between scheduling and the capacity of the airports, which leads to flight delays (Santos, 2018).

In theory, scheduled flights follow a preset allocated time which is planned in a long-term perspective. However, it is very difficult to precisely match the allocated schedule with the actual time because there are many aspects involved in this process which can vary during a daytime perspective. Specifically, upon arrival, three processes are needed for the aircraft which area subjected to delays. Those are: (i) landing on a specific runway; (ii) service on the ground; which varies based on the type of plane that is serviced, weather conditions and type of passenger, and (iii) departure through a take-off runway.

In this context, the arrival or departure rate of airplanes at an airport is often non-deterministic. The service rates of aircraft are not identical and independently distributed. Therefore, the probabilistic distributions of these services are very difficult to determine and the total time required for operations is highly variable. This allows to model an airport as a queuing system (Bezerra & Gomes, 2016; Ignaccolo, 2003; Mehri, Djeme, & Kammoun, 2008). According to Gross et al. (2008), six basic characteristics of queueing processes provide an adequate description of an airport queueing system which are arrival pattern of airplanes, service pattern, queue discipline, system capacity, number of service channels and number of service stages.

Slot control arose as a strategic option to support management challenges due to the difficulty of managing the scheduling complexity process in a scarce capacity context added to the need for a correct treatment to the congestion and delay problem. The IATA defines slots as a permission given by a coordinator in charge for a planned operation to use the entire airport infrastructure for arrivals and departure at a specific time and date (IATA, 2017). Additionally, IATA denominates airport coordination as way to manage shortages in the airport capacity by applying a set of rules that guide airports in slot management and allocation named WSG (Worldwide Slot Guidelines).

Coordination of slots involves allocating limited or restricted airport capacity to airlines or other air operators with the objective of ensuring a viable operation of airport and air transport. The process of suiting airline requests with specific slots are constrained by available capacity. This measure is expressed as declared capacity which specify the airport slot availability for arrival and departures during each coordinated time interval. The coordination time interval is the core for capacity determination and slot allocation.

In short, the main objective of airport coordination is to ensure the most efficient use of airport infrastructure maximizing the benefits for the vast majority of airport users. This main objective is not always accomplished because of the intricacy of the slot allocation process added with a lack of decision support system. As a consequence, there is a large need for efficiency improvements in slot allocation process worldwide (Zografos, Salouras, & Madas, 2012).

Operational research can be applied as an instrument to handle this complex challenge. Operational research techniques have played an important role in handling such complexities since its tools have the capacity of improving operation efficiency by modeling a critical operation in a mathematical manner. In many cases, these tools are used to support decision making. It is commonly applied to problems that concern how to conduct and coordinate operations within an organization (Hiller & Lieberman, 2010).

Airlines have been using operations research techniques since the 1950s (Barnhart & Talluri,1997). Operations research models have had a tremendous impact on planning and managing operations within the airlines. A large part of the problems that airlines face can be translated into network and integer programming models (Bazargan, 2016). In the specific case of enhancing slot allocation efficiency there are some studies that allow for this challenge to be dealt with (Makris, 2018; Zografos et al. 2012). This study falls in this direction and hopes to accomplish a more efficient outcome in the area of slot control by utilizing operational research.

It is important to stress that slot coordination is not a solution to the fundamental problem of the lack of airport capacity. Coordination should be seen as a temporary solution to manage congested infrastructure until the implementation of a long-term solution to expand airport capacity.

ANAC started coordinating slots in Brazil during 2009 at Guarulhos Airport. Currently, ANAC is responsible for coordinating five airports in Brazil which are Congonhas (CGH/SBSP), Guarulhos (GRU/SBGR), Pampulha (PLU/SBBH), Recife (REC/SBRF), and Santos Dumont (SDU/SBRJ) (ANAC,2019).

For the development of this research Congonhas Airport was selected. Opened in 1936, Congonhas Airport is the oldest in Brazil still operating commercial flights. In mid-1957 it was the world's third air cargo airport and in 1990 it was the busiest airport in Brazil. In addition to these features, the interest in analyzing the delay variables at Congonhas Airport is motivated by three characteristics that make the airport unique: (i)It is the 3rd busiest airport in Brazil and the only one of the six busiest that is still operated by public initiative through INFRAERO; (ii) Operates only domestic flights, being the 2nd busiest in the country in domestic terms; and (iii)It is located within the city center of São Paulo, the largest in the country, and operates with time limitations for landings and takeoffs (06:00h to 23:00h).

The criticality of this airport requires efficient planning and a continuous improvement study focused on a decision support system that accommodates IATA guidelines supplemented with ANAC adaptations and that further helps to achieve the optimal solution for slot allocation. The research problem consists of the appropriate slot allocation minimizing the total displacements while considering IATA/ANAC regulations, airport restrictions and air carrier schedule efficiency. Based on that, the research question was defined: How to improve the efficiency of slot allocation in a congested Brazilian airport?

Objectives

To aid the slot allocation into making the most optimal decision, this study has the objective of implementing a slot optimization model to support the decision-making problem, taking into consideration the IATA/ANAC scheduling rules, coordination procedures and operational constraints. A decision support system leads to a more efficient schedule. The specific objectives for this project are:(i) achieve the minimization of the difference between the scheduled slot and the actual slot time; (ii) produce a more efficient slot allocation that will lead to a fairer schedule in a tactical perspective, being fair defined as a more precise slot allocation in terms of a medium time horizon schedule planning.

Methods

The conception and development of this case study involves a set of steps that may be described in the sequence: Definition of the Problem and Data Collection, Implementation of the Model, Solution of the Model, Validation of the Model and Analysis of Results (Taha, 2008).

Definition of the Problem and Data Collection

The first action involved defining the problem addressed by the optimization model proposed here. A number of studies and reports involving the current state of airports worldwide were studied (Makris, 2018; Zografos et al., 2012) to assess the present-day situation and to identify the causes and possible actions to the congestion problem and delays faced in the context of Congonhas Airport. In that case, the demand management approach through slot coordination was chose to be the method to be studied.

Slot coordination is a very complex and relatively new process in Brazil having started in 2009 on Guarulhos Airport (GRU/SBGR). There is ample room for efficiency improvements in the allocation process. This difficulty of managing slot allocation is apparent when the airlines have to deal with a complicated allocation process involving multiple criteria, rules and priorities. Furthermore, there is limited decision support available to do this process in the country.

The current practice is based on ANAC Standards (ANAC, 2018) which stipulates some minimum targets to control and manage which flights are going to continue having the historic of slots for the next season. The targets are set as a minimum of 80% of flight regularity to all the coordinated airports in Brazil in exception of Congonhas airport which has a minimum of 90% of flight regularity (Art. 1º, § 1º, Inciso VII[1]). Also, ANAC states a maximum deviation tolerance of 15 minutes for arrival and departure. This implies penalizations for flights when there is a tendency of displacement occurring during a season, simply put when frequent slot misuse occurs (Art. 1º, § 1º, Inciso VIII). In Congonhas airport (CGH/SBSP), Guarulhos International Airport (GRU/SBGR) and Santos Dumont Airport (SDU/SBRJ) slot deviation are strictly monitored. During the season, ANAC keeps supervising and notifying the airlines in case they are delaying or anteceding some flight with certain frequency. After receiving two notifications and not taking action, the slot loses its history; which means the airline will lose the slot for the next season. This represents a big loss for the air company, especially in these main airports of Brazil in which almost all the slots are already occupied. In this context, this research focuses in implementing a slot optimization model in a critical airport in Brazil allowing for a more efficient allocation outcome that would imply less difference between the allocated and actual flight.

In this step data was collected to be analyzed in addition to defining the problem. Gathering relevant data is needed both to gain an accurate understanding of the problem and to provide the needed input for the mathematical model (Hillier & Lieberman, 2010). The main data source is Voo Regular Ativo (VRA) which is collected from ANAC. This database presents all the Active Regulated Flights in Brazil. More specifically it is composed by information of scheduled airlines, listing the status of the flights (i.e. cancelled or realized), flight times, and delay codes provided by the airlines. ANAC openly provides the historic Active Regular Flight series for studies and analysis. The period collected was S18 (Summer 2018) until W18 (Winter 2018) englobing months from March 2018 to March 2019. Since this selected period represents a whole year, data mining was applied to work as a funnel mechanism to determine the two critic flights to be applied in the slot optimization model. Tools such as filtrations and percentages were used to process the data and identify some patterns. Data mining is a very useful tool used to discover interesting patterns and knowledge from large amounts of data (Han & Kamber, 2011).

Initially, with the support of software R the flights from Origin/ Destination in São Paulo/Congonhas (SBSP/CGH) were selected from the flight pool. Each row consists of one regular flight and each column is one information about it. Then all the flights done by GOL Airlines were filtered from the total amount of flights from and to Congonhas. The next step involved making separate counts of total flights

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in Brazil, total flights in Congonhas and total GOL Airlines flights operating in Congonhas for each month.

This data allowed for the calculation of the percentages of Congonhas flights within Brazil and the percentage of GOL Airlines flights within Congonhas as described the Table 1. The importance of Congonhas Airport can be demonstrated by its representation of approximately 18% of Brazil's flights and the large impact that GOL airlines has by summing up to 44% of all flights to and from CGH.

Table 1
Brazil Air Traffic Historical Data

	Mar 2018	Apr 2018	May 2018	Jun 2018	Jul 2018	Aug 2018	Sep 2018	Oct 2018	Nov 2018	Dec 2018	Jan 2019	Feb 2019	Mar 2019
Flights in Brazil	90789	79781	83754	80302	90216	84388	80919	83647	80025	87628	91817	79526	83062
Flights in CGH	15431	14518	15311	14360	15623	15459	14557	15446	14690	15329	15801	14061	14859
Gol flights CGH	6729	6337	6705	6374	6861	6719	6293	6754	6535	6802	7017	6176	6450
% CGH /Brazil	**17%**	**18%**	**18%**	**18%**	**17%**	**18%**	**18%**	**18%**	**18%**	**17%**	**17%**	**18%**	**18%**
% Gol /CGH	**44%**	**44%**	**44%**	**44%**	**44%**	**43%**	**43%**	**44%**	**44%**	**44%**	**44%**	**44%**	**43%**

Source: Elaborated by the author.

Table 2
Congonhas Airport Historical Data

	Mar 2018	Apr 2018	May 2018	Jun 2018	Jul 2018	Aug 2018	Sep 2018	Oct 2018	Nov 2018	Dec 2018	Jan 2019	Feb 2019	Mar 2019
Total cancelations /delays	6607	2050	2942	2795	3808	2142	1572	2247	3547	3747	3845	6494	6693
Total Gol Airlines delays	1335	1133	1276	1642	1899	1118	964	1354	2013	2364	2438	2403	2155
Total cancelations /delays	43%	14%	19%	19%	24%	14%	11%	15%	24%	24%	24%	46%	45%
Total Gol Delays	20%	18%	19%	26%	28%	17%	15%	20%	31%	**35%**	**35%**	**39%**	33%

Source: Elaborated by the author

Table 2 shows total cancelations and delays in CGH due to all operating airlines and also the ones resulted by GOL airlines. It also expresses the percentages of delays and cancelations generated by all the operating airlines in CGH, and the percentages of total delays caused by GOL in CGH. Three critical months were selected to be further studied based in the monthly percentages of total GOL delays in CGH. They are DEC-18, JAN-19, FEB-19.

Those three months were gathered in one database and created four auxiliary columns. They are departure absolute delay, departure status, arrival absolute delay and arrival status. This consolidated database was considered the Data Warehouse for the further optimization model. Han and Kamber (2011) described data warehouse as a repository of multiple heterogeneous data sources organized under a unified schema at a single website to facilitate management decision making.

The departure and arrival absolute delay were both calculated from the comparison between the expected and actual flight times. The departure and arrival status columns described which delays were penalized. The penalized delays show an absolute delay equal or greater than 15 minutes. Based on that, the columns were sorted by highest number of penalizations both in departure and arrival status. Thereafter, the top three flight in terms of penalizations in arrival and departure were selected. For each of those top penalized flights, a detailed analysis was conducted to determine the flights that had a higher percentage of justification codes in which the responsibility was attributed to the airline. Higher percentages of internal code were used as evidence that a flight had room for efficiency improvements.

Flights GOL 1389 and GOL 1666 were selected due to being crucial for the arrival and departure processes respectively. GOL 1389 originates in Vitoria, ES (SBVT) and lands at Congonhas, SP airport (SBSP). Scheduled departure time is 13:25hrs at SBVT and arrival at 14:55hrs on SBSP with an estimated flight time of 1h30m. GOL 1666 originates in Congonhas, SP airport (SBSP) and lands at Fortaleza, CE (SBFZ). Scheduled departure time is 14:20hrs at SBSP and arrival at 17:45hrs on SBFZ with an estimated flight time of 3h25m.

During this phase the declared capacity of Congonhas was additionally collected from ANAC. Declared capacity is derived from various elements of the airport, such as the runway capacity, the passenger terminal capacity, the apron area, different types of movements (arrivals or departures) or flights (domestic or international) as well as environmental or political restrictions (Morisset, 2010). The airport capacity constraints are typically declared as the number of movements which can be handled by the runway system in a given period. The runway capacity was collected from the Congonhas Airport Declared Capacity which provides the total limits per hour. Illustratively, the airport capacity during the time interval 06:00-07:00 is up to 32 movements (TOT). The limits for arrival (ARR) and departure (DEP) per hour were supplementary collected from the Online Coordination System (OCS) since the Congonhas declared capacity does not provide this information.

A challenge in the optimization problem was the definition of sub limits of 5 minutes for each slot. Since the duration of the coordination time interval is provided in hours, it had to be converted in sub limits of 5 minutes coordination time interval. This conversion of time was done based on the declared capacity table from Brussels airport (Morisset, 2010), chosen due to similarities with the Brazilian Airport. Data with 5 minute and 1-hour time interval was then extracted from the Brussels airport declared capacity table. Proportionality, between 5 and 60 minutes capacity in Brussels, was observed and so applied to the time data of Congonhas

Airport (CHG/SBSP). As an example, for the hourly time interval 06:00-07:00 (ARR=19, DEP=22, TOT=32 in CGH) the values of proportionality observed were ARR=15%, DEP=15%, TOT=22% so was applied to the 5 minute interval resulting ARR=3, DEP=3, TOT=7, for 5 minute slot in CGH. This was the procedure applied to determine the 204 set of airport capacity constraints, with 5-minute coordination time intervals.

Implementation of the Model

Furthermore, the mixed integer linear model (MILP) developed by Zografos et al. (2012) was implemented. The model uses a series of sets and parameters that describe several indicators that must be used for the calculations. Some notations and conventions will be introduced to simplify the problem statement:

Sets

$T = \{0, \dots, n-1\}$: Defines a set of 5-minute coordination time intervals per day indexed by t.

D = (d = 1;…; 7): States the set of calendar days of week, starting on Sunday = 1, Saturday = 7, constituting the period to be scheduled.

M: Set of request movement, types $m = \{ARR, DEP\}$: M comprises pairs of movements, arrival (ARR) or departure (DEP).

$C = \{1, \dots, C\}$: Set of airport capacity constraints, indexed by c.

T_c: Set of coordination time intervals over which the constrain c is checked. Represents the duration, expressed by the number $t_c > 0$, for each $c \in C$.

$T_C^S = \{t \in T | s \leq t \leq s + t_C\}$: Set of consecutive coordination intervals over which the constraint c is checked, in the time period $(s, s + t_c)$ of length $t_c > 0$. $s \in [0, n - t_c + 1)$ is defined as a starting time s.

Parameters

u_c^{ds}: Capacity of constraint c for day d and coordination time interval s. The capacity value u_c^{ds}, determine the maximum number of movements that can be scheduled by a fixed duration (e.g., 5, 15, 60 minutes). Meaning that this rolling capacity requires that the number of movements allocated to consecutive time intervals within T_C^S should be smaller than the capacity value u_c^{ds}.

$P\{a \in M, d \in M\}$: Set of flight pairs (a, d) where arrival a corresponds to departure d., such that there is a connection between a and d.

t_{ad}: Minimum turnaround time corresponding to the movement pair a,d. This minimum time is represented by $t_{ad} \geq 0$, for each pair of movements.

$a_m^d \in \{0,1\}$: This parameter symbolizes the days on which each movement operates, it takes value 1 if movement m operates on day D, zero otherwise.

$b_{mc} \in \{0,1\}$: Designate the units of capacity consumed by a movement m. It takes value 1 if movement m is an arrival (departure) and the constraint c applies to arrivals (departures) only or total movements.

Decision Variable

$X_m^t \epsilon \{0,1\}$ — It takes 1 if m (a or d) is allocated to interval *t*, zero otherwise. This decision variable also appears in the objective function. This allocation of movement m to coordination intervals (t) is determined through binary decision variable (x_m^t).

Objective Function

f_m^t: — Represents the cost of allocation movement m to interval t. Calculated as $|t - t_m|$ where t_m is the time interval originally requested form.

The exact model formulated by Zografos et al. (2012) that is going to be implemented in this research, is the following:

$$MIN \sum_{m \in M} \sum_{t \in T} f_m^t . X_m^t \qquad (1)$$

$$Subject\ to \quad \sum_{t \in T} X_m^t = 1, \qquad m \in M \qquad (2)$$

$$\sum_{m \in M} \sum_{t \in T_c^s} a_m^d . b_{mc} . X_m^t \leq u_c^{ds}, \qquad c \in C, d \in D, s \in T_c \qquad (3)$$

$$\sum_{t \in (0,K)} X_d^t + \sum_{t \in [k - t_{ad}, n]} X_a^t \leq 1 \quad \{a, d\} \in P, \qquad ks \in (t_{ad}, n) \qquad (4)$$

The object function (1) attempts to minimize the total displacement, which means minimization of the total absolute difference between the requested and allocated time. Three constraints were applied to this function. The first constraint (2) states that every movement has to be allocated to exactly one coordination time interval. The second constraint (3) ensured that the total movement consumption has to obey the airport´s declared capacity. The last constraint (4) imposes that an arrival has to be separated from departure by at least a specified number of slots.

As previously described, the period of each coordination time interval was set to equal 5 minutes. Since Congonhas Airport works from 06:00h to 23:00h the T equal 204 coordination time intervals per day. The total number of days refers to the slots requested by GOL airlines for the precise scheduling period, involving the critical months (i.e. DEC-18, JAN-19, FEB-19). The exact scheduling period analysis was completed during that season ranged from December 1st to February 28th, spanning a horizon of 90 scheduling days. Regarding the precedence constraint (Eq. 4), the minimum turnaround time was set equal to 30 minutes referring to 6 coordination time intervals.

All requested pairs of movements already satisfied this restriction; every requested arrival of the initial data set was separated at least 6 time intervals from the respective departure. This was important in the course of the model's application; if the case was otherwise different and arrivals were separated from departures by a smaller number of intervals, the precedence constraint would pose additional difficulties in the solution process.

The slot optimization method described by Equation 1 to 4, can be viewed as an optimization matter which can be generally summarized as follows: (i) number of airline slot requests, during the operating season (W18); (ii) the set of restrictions arising from the Declared Capacity of the Congonhas Airport; (iii) a combination of slot allocations (i.e. balance between capacity and demand); and (iv) minimizes the gap between the planned timetable and the allocated flights. The idea is that each slot allocated in a delay situation, triggers an additional disruption of the schedule which "penalizes" planned slots.

The proposed approach was implemented using the add-inn OpenSolver for Excel which is a general-purpose tool for optimization computing. This software extends Excel’s capabilities with a more powerful linear solver suitable for handling linear programming and mixed integer programming models. The main criteria for choosing this computational tool was its compatibility with spreadsheet models built with Excel's Solver enhancing the program’s data size limits. Subsequently, the data preprocessing and graphical analysis were made with Microsoft Excel spreadsheet. OpenSolver uses the Open Source, COIN-OR CBC (linear) optimization engine. COIN-OR means Computational Infrastructure for Operations Research and CBC (Coin-or Branch and Cut) is an open-source mixed integer programming solver. The results have been obtained on a machine with an Intel Core i7-3537U CPU at 2.10 GHz with 8 Gb of RAM memory under Microsoft Windows 8.1, 64-bit operating system and 460 Gb of disk space.

Solution of the Model

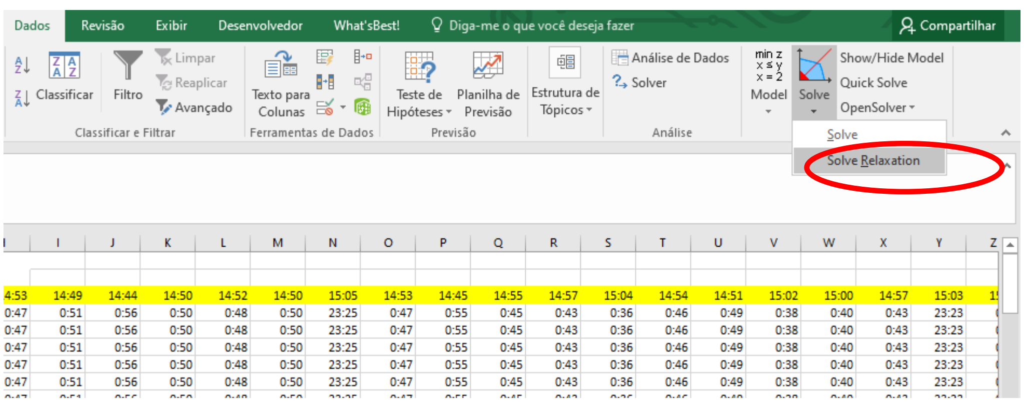
The same approximation of Zografos et al. (2012) was used (i.e. the Linear relaxation approach) in order to deal with the dimensionality of the problem. The sub-routine used to produce this process is shown in Figure 1. OPT denotes the current model (1)– (4), which describes linear relaxation. OpenSolver provides a menu item to solve the relaxation of an integer linear program, as shown in Figure2.

Figure 1
The sub-routine for linear relaxation.

Add variables to OPT
Add assignment rows (2) to OPT
Do
    Solve OPT as a linear program
    Remove inactive rows (3) or (4) from OPT
    Identity violated capacity rows (3)
    Identity violated turnaround time rows (4)
    Add violated rows to OPT
***While** at least one violated row has been identified*

Source: Zografos et al. (2012).

Figure 2
Solving the Relaxation in OpenSolver.

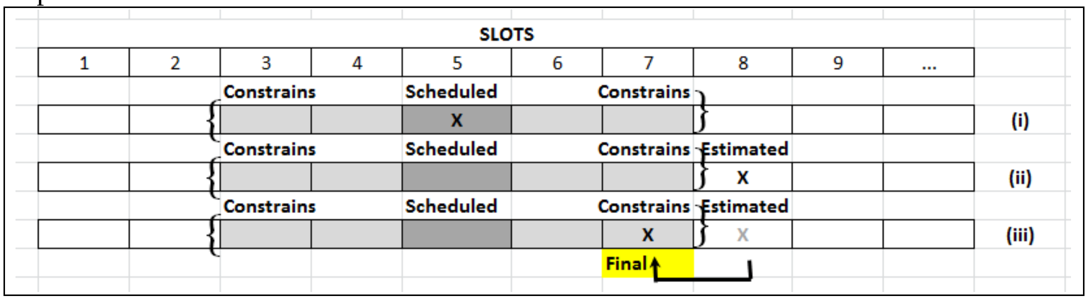


Source: Elaborated by the author.

The following is a brief description of the steps. Additionally, Figure 3 illustrates the phases in which the model (1)-(4) runs:

i Using objective function (1) and constraints (2)-(4), a single objective slot allocation model is constructed and solved. The model's optimal solution corresponds to the minimum total schedule displacement;
ii This model is solved iteratively and sometimes violated slot may arise;
iii Final Optimal Solution.

Figure 3
Optimal solution of the slot Allocation Problem.



Source: Elaborated by the author.

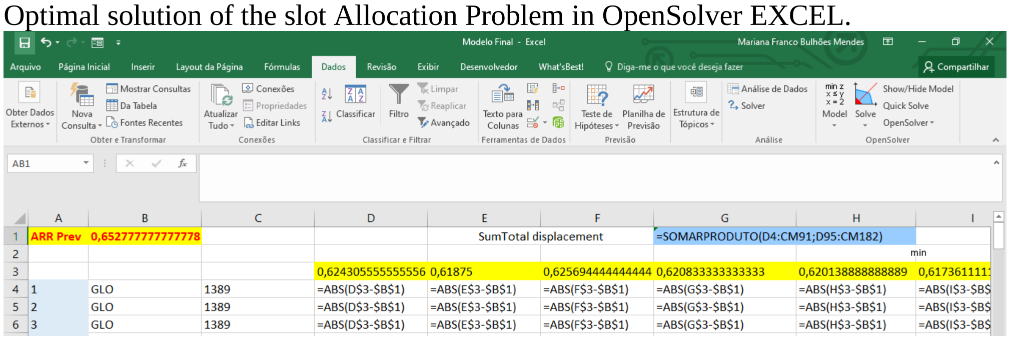
The model used for minimizing the cost of allocation involved with airline flights in available slots was constructed around the binary decision variable (x_m^t), as follows:

(x_m^t) = 1 if airline flight is allocated to the slot *t*;
(x_m^t) = 0 otherwise.

The objective function that represents the cost of allocation movement *m* to interval *t*, can be expressed as the SUMPRODUCT of the decision array and the binary decision variable values expressed by another array and illustrated on Figure 4. For modeling purposes, it’s convenient to convert all information into a conflict array, shown in Figures 5 e 6 as part of the full model. Figure 5 correspond to an array with cost of allocation, calculated as $|t - t_m|$ where t_m is the time interval originally requested form. Figure 6 represents the possible assignments of flights, with entry of 1 or 0.

The model was solved by using the button on the ribbon (Figure 2). OpenSolver then analyzed the spreadsheet and extracted the optimization model, which was then written to a file and selected the CBC engine to output the solution, as shown in Figure 7. The result was then automatically loaded back into the spreadsheet.

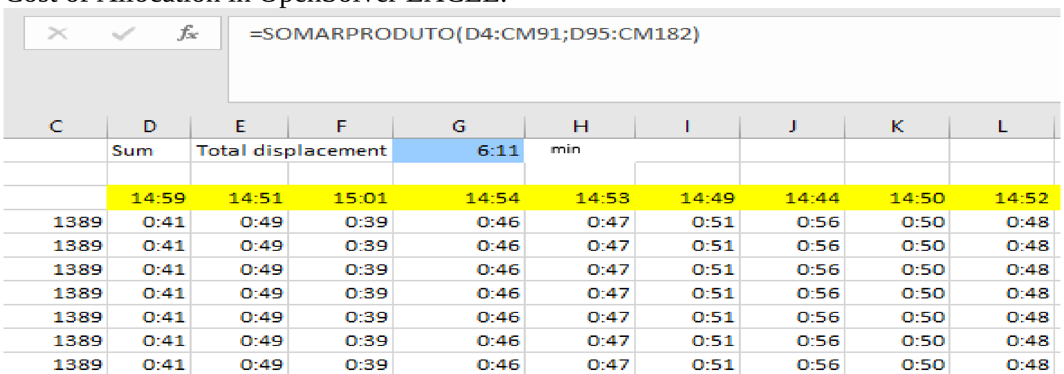
Figure 4
Optimal solution of the slot Allocation Problem in OpenSolver EXCEL.



Source: Elaborated by the author.

Figure 5

Cost of Allocation in OpenSolver EXCEL.

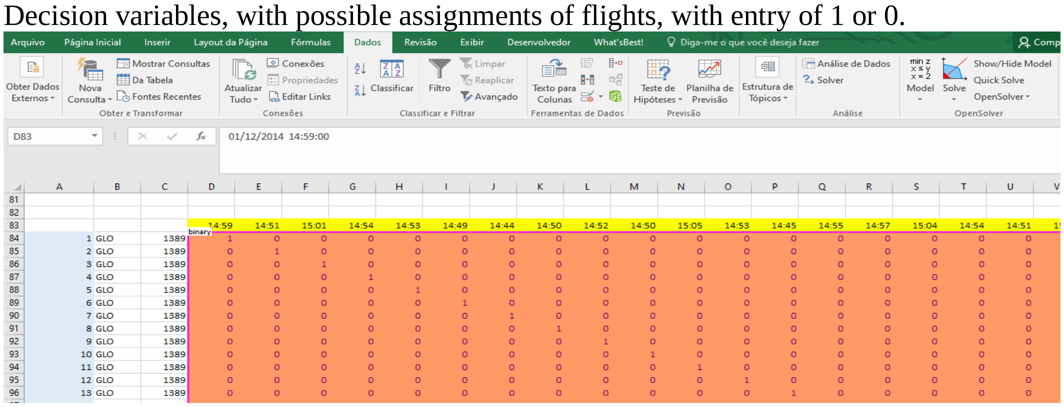


C	D	E	F	G	H	I	J	K	L
	Sum	Total displacement		6:11	min				
	14:59	14:51	15:01	14:54	14:53	14:49	14:44	14:50	14:52
1389	0:41	0:49	0:39	0:46	0:47	0:51	0:56	0:50	0:48
1389	0:41	0:49	0:39	0:46	0:47	0:51	0:56	0:50	0:48
1389	0:41	0:49	0:39	0:46	0:47	0:51	0:56	0:50	0:48
1389	0:41	0:49	0:39	0:46	0:47	0:51	0:56	0:50	0:48
1389	0:41	0:49	0:39	0:46	0:47	0:51	0:56	0:50	0:48
1389	0:41	0:49	0:39	0:46	0:47	0:51	0:56	0:50	0:48
1389	0:41	0:49	0:39	0:46	0:47	0:51	0:56	0:50	0:48

Source: Elaborated by the author.

Figure 6

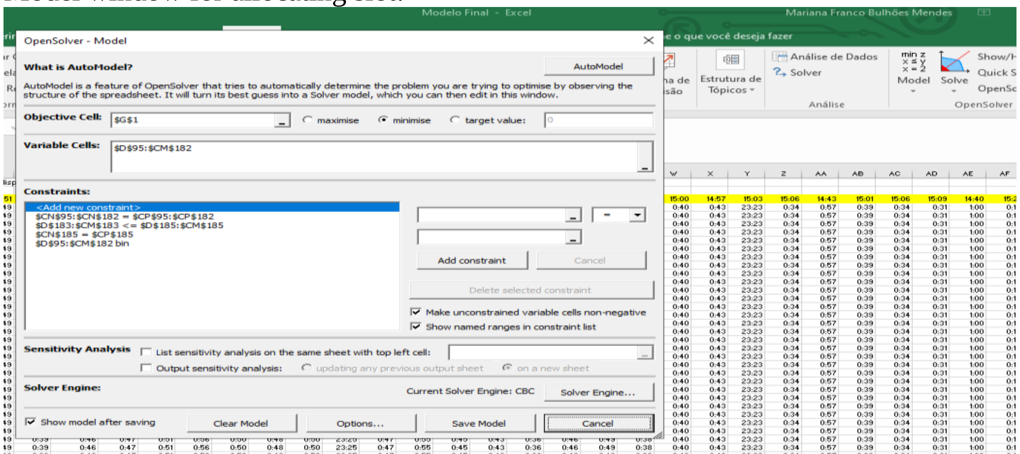
Decision variables, with possible assignments of flights, with entry of 1 or 0.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
81																					
82																					
83				14:59	14:51	15:01	14:54	14:53	14:49	14:44	14:50	14:52	14:50	15:05	14:53	14:45	14:55	14:57	15:04	14:54	14:51
84	1	GLO	1389	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	2	GLO	1389	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	3	GLO	1389	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	4	GLO	1389	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	5	GLO	1389	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
89	6	GLO	1389	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
90	7	GLO	1389	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
91	8	GLO	1389	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
92	9	GLO	1389	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
93	10	GLO	1389	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
94	11	GLO	1389	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
95	12	GLO	1389	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
96	13	GLO	1389	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

Source: Elaborated by the author.

Figure.7
Model window for allocating slot.



Source: Elaborated by the author.

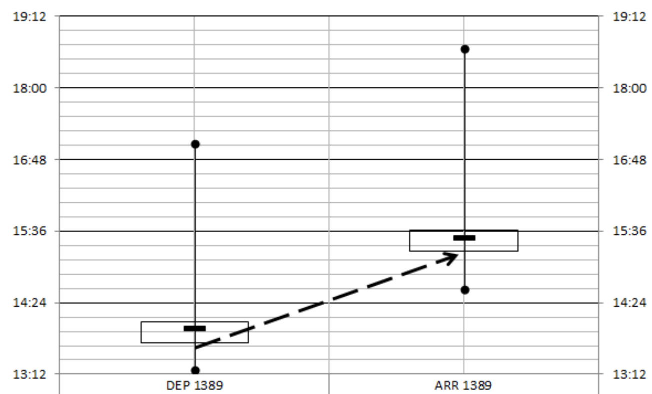
Results & Discussion

As a final result the reallocated slot for the analyzed flight GOL 1389 which was scheduled for arrival in CGH at 14:55 hr is 15:15 hr therefore minimizing the total displacement from 03:50hr to 2:29hr. Additionally, the reallocated slot for the analyzed flight for flight GOL 1666, scheduled for departure in CGH at 14:20hr hr is 14:40hr therefore minimizing the total displacement from 03:16hr to 1:03hr.

Validation of the Model

To ensure comparability of results a boxplot with the real data was created in an effort to describe the current movement (arrival and departure) behavior and compare it with the optimal solution in order to see if represents the reality. Knowing the behavior of the real data made it possible to analyze the validity of the optimized solution. The boxplot is synthesized in Figure 8 describing the departure (SBVT) and arrival (SBSP) data for flight GOL 1389.

Figure 8
Boxplot for flight GOL 1389.

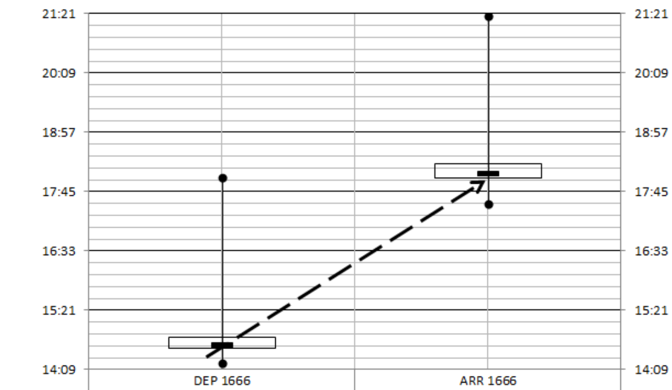


	DEP 1389	ARR 1389
Q2 (Median)	13:57	15:28
Q1 (25%)	13:44	15:16
Max	17:04	18:40
Min	13:16	14:37
Q3 (75%)	14:05	15:37

Source: Elaborated by the author.

Figure 9 illustrates departure (SBSP) and arrival (SBFZ) data for flight GOL 1666, with a similar interpretation. The comparison between the real data and optimal solution was based on the described boxplots. The verification showed that the optimal solution for GOL flights 1389 has it value around the first quartile of the boxplot and in the case of GOL 1666 the solution is around the average. For both flights the optimal output is satisfactory meaning that the solution is giving valid results. Therefore, if the optimal solution is applied there will be less displacement and not much impact on the marketing strategy applied to the airline network due to the optimal solution dispersing negligible amounts in regards to the planned original schedule.

Figure 9
Boxplot for flight GOL 1666



	DEP 1666	ARR 1666
Q2 (Median)	14:39	18:07
Q1 (25%)	14:36	18:01
Max	18:03	21:19
Min	14:17	17:31
Q3 (75%)	14:48	18:19

Source: Elaborated by the author.

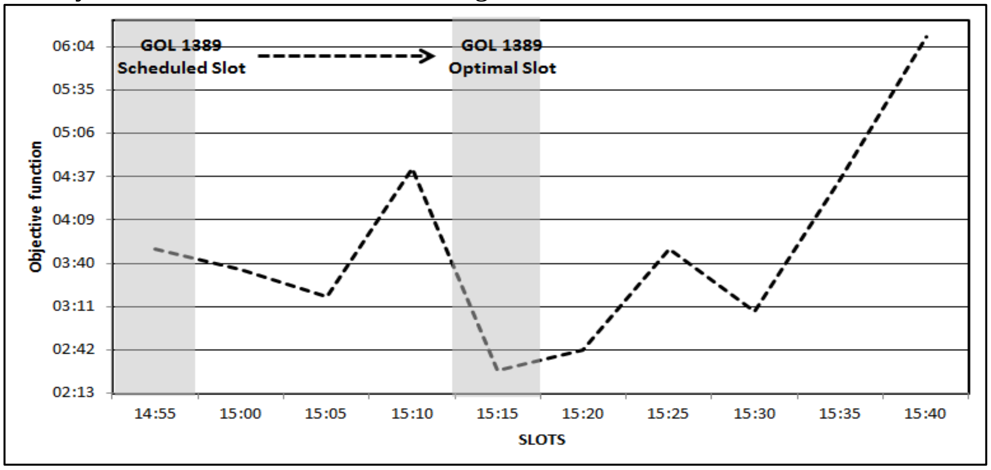
Analysis of Results

With the purpose of measuring the efficiency of the proposed model implementation from a decision-making point of view; its results were compared to the actual allocation outcomes according to the current slot allocation practice.

Considering the minimum turnaround time of 30 minutes, for each pair of movements (ARR and DEP), corresponding to 6 slots of 5 min/each, the question that arises relates to how sensitive is the sum of time displacement (Objective Function) to changes in airport slots in this 30 minutes' interval. In this context, sensitivity analyses are used to trace the effect on objective function changes due variations in airport slots. To do this, the cell was varied from the initial slot (i.e. 14:55 for GOL flight 1389), during an interval of 30 min with 5 min steps. Figures 10 and 11 show the results describing the Objective Function in the two flights studied. In both flights the objective function ($\boldsymbol{f_m^t}$) is represented as a penalizing function for the minimization problem, expressed for different slots. The x-axis is the scheduled slot time, and the y-axis is the value of the penalty function. This function is expressing in both flights the minimization of the total displacement between the historic data to the optimal solution.

It can be clearly observed that the optimal solution in both cases provides a smaller penalty meaning that the suggested solution brings a smaller displacement. The results represent a 35,22% and 67,83% improvement with respect to slot allocation efficiency for flights Gol 1389 and Gol 1666 respectively. From these results, it is clear that the proposed approach produces superior results in comparison to those supplied by the current allocation practices. This slot allocation improvement allows for a first evidence towards the applicability of this model.

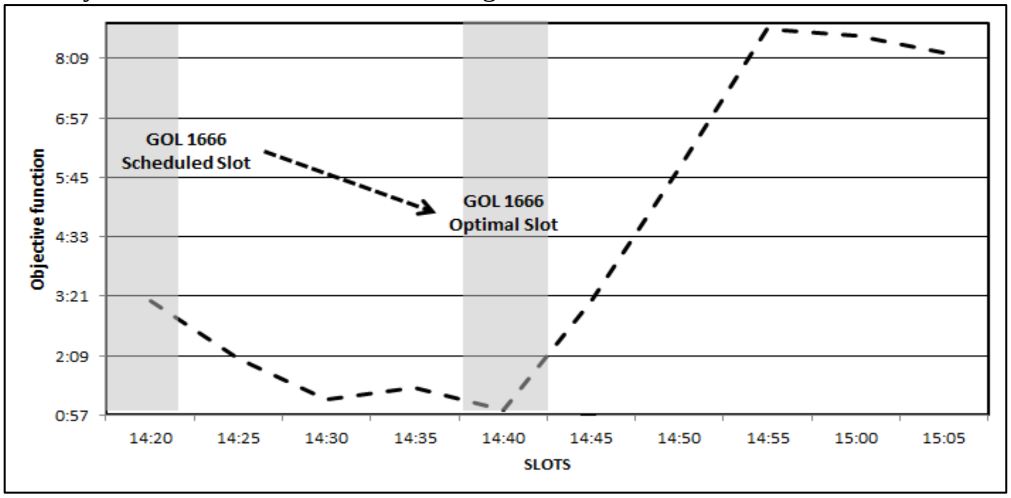
Figure 10
Penalty function of slot allocation for flight GOL 1389



Source: Elaborated by the author.

This is added to the large potential for improvements concerning the allocation efficiency at Brazilian airports which are suffering from severe congestion problems along with complicated rules and principles.

Figure 11
Penalty function of slot allocation for flight GOL 1666



Source: Elaborated by the author.

A sensitivity analysis was done by changing the capacity parameters and observing its consequences in the object function along with the sensitivity analysis described above by the changes in airport slots illustrated by Figure 10 and Figure 11. This complementary analysis was done varying the declared capacity in the interval of 7 to 13 slots per 5 minutes, already considering the optimal solution of 15:15 hr and 14:40 hr for GOL flight 1389 and Gol flight 1666 respectively. For both flights the increase of the declared capacity parameter by about 85 % resulted improvements in the total objective function close to 45%. More specifically the increased capacity values generated a 1:25 hour total displacement (as compared to before 02:29) away from requested slots for Gol flight 1389 and 0:38 hour (as compared to 01:03) for Gol flight 1666. It is important to notice that a change in the declared capacity involves complex multiparty procedures, not dependent on the air company.

This study has limitations; this model only focuses on runway capacity and its optimization. Airport capacities (e.g. gate availability, baggage handling capacity, aircraft size, etc.) are not taken into account. Furthermore, it is assumed that an aircraft will depart on the same day of arrival, so it is not possible to depart the next day.

Conclusion

Brazil as a country, has not been able to yet accommodate the significant growth in air transportation experienced worldwide; due to its historical lack of competitiveness and productive pressure as well as insufficient investments within infrastructure combined with public and private corruption. This all generates a large imbalance between demand and supply causing serious congestions and delays (Wanke, 2012). Recently, scarce capacity started being expressed in slots and allocated on the basis of a complex set of administrative rules, restrictions, and priorities set out by IATA and further complemented by ANAC regulation in level three airports located in Brazil. However, the current slot allocation practice does not reach the efficient schedule, mainly because of slot inefficiency e slot misuse.

This research focused in implementing the single-airport slot optimization model developed by Zografos et al. (2012) in an effort to allocate slots more efficiently while facing the need of mitigating the congestion problem and therefore minimizing delays in a single airport. As described, this paper focused in Congonhas Airport and more specifically on Gol airlines flights GOL 1389 and Gol 1666. The outcomes of the model implementation for both flights better accommodate slots which in turn mean less difference between the scheduled and actual flights, expressed in the form of schedule displacement metric (i.e., difference between requested and allocated slot times).

In summary, the optimization of this processes means improved slot utilization rates allowing a more efficient use of limited airport capacity with clear benefits for airlines, airports passenger and the flow of air transport at large. This optimization model should supersede the empirical practice while allocating slots. It is aligned with the IATA standards and can easily be adapted with the local legislation. The model deals successfully with the trade-off between performance and execution viability as it draws on current practice to bring about notable improvements in the allocation system quality.

In this study the turnaround time was taken as premise to be 30 minutes. For higher accuracy in further studies the turnaround should be more realistic and adapted to each situation. There is high importance of the turnaround time to the efficiency of the allocation process. An ideal turnaround time is very hard to determine since it involves many different areas of the airline which might have different perspectives about it depending on sector of the company. An even more effective output for slot optimization can potentially be achieved by taking into consideration the interconnection between the airline areas with respect to optimal turnaround time. Also, future research directions should involve the analyses of the optimal output bearing in mind the whole network in order to manage the heavy interdependence between airports.

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