Enhancement of Airport Collaborative Decision Making through Applying Agent System with Matching Theory

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ABSTRACT
The Collaborative Decision Making (CDM) paradigm attempts to improve the exchange of information among the various stakeholders involved in Air Traffic Management (ATM). It is aimed at efficient decision making in airport management. Although the processes of CDM are considered mature and well accepted, in many cases it usually the focus is on the information sharing and is still not able to simultaneously involve essential agents such as Air Traffic Control (ATC) agency, airlines, and airport managers in the decision making. This study uses the matching approach of Game Theory to construct a two-sided matching market model for slot allocation in the Compression step while taking into account Ground Delay Programs (GDP). Our proposed model, Deferred Acceptance CDM (DA-CDM), assigns each flight to each slot through a "one-to-one" relationship, respecting the preferences of each allocation, leading to a stable result. It is applied to evaluate the classic CDM and Airport CDM processes with a group of analytics data. Our results show that the new allocation mechanism provides a stable and satisfactory matching of the flights with the slots in A-CDM procedure.

Categories and Subject Descriptors
I.2.11 [Artificial Intelligence]: Distributed Artificial Intelligence – Intelligent agents, Multiagent systems; I.6.5 Computing Methodologies, Simulation and Modeling, Model Development.

General Terms
Algorithms, Management, Design, Theory

Keywords
Multiagent Systems, Collaborative Decision Making, Ground Delay Program, Matching Theory.

1. INTRODUCTION
Over the last few years, the increasing global demand for air transportation has greatly increased the complexity of the air traffic management scenario [5]. This situation enforces new integration challenges faced by several stakeholders, such as regulation agents, airlines, airport management companies, traffic managers, flight crew, passengers, and aeronautical system's manufacturers, among others [17].

Some processes, such as those aimed at reducing congestion in specific locations in the air scenario, involves the definition of delays for aircrafts on ground and are carried through the Ground Delay Program (GDP). This process, based on Collaborative Decision Making (CDM) concepts, brings the need of reallocating aircraft from the scheduled slots originally established for the runways of the affected airports [27].

Besides its simplicity of concepts, the current CDM model involves a limited number of entities in the decision-making process [6]. When using traditional CDM model and considering the existence of distinct interests on delays applied to aircraft, it is difficult task to get the satisfaction of all stakeholders who affect and are affected by delays generated by a GDP [23].

In this context, the matching approach of Game Theory can be used to construct the model of markets with the satisfactory results regarding the dispute for resources. By this approach, the preferences of all participants in that market are taken into account [25].

Regardless of the application area, a market can be modeled in order to obtain results that account for the different goals multiple agents, such as students, schools, doctors, hospitals, patients, passengers, airlines, and airports, among others. Moreover, the modeling constraints on organ donation markets in the 2000s allowed the correct treatment of a wide variety of features in more complex scenarios [21, 22].

In situations involving the departure coordination, traffic, and arrival of multiple flights through Air Traffic Management (ATM), mathematicians, economists, engineers, computer scientists, and researchers from various fields have developed Artificial Intelligence, multi-agent systems, and models based on Game Theory, among others. These models are applied in domains that involve problems of coordination and competition for resources [1, 3, 9, 28, 29].

However, most of the studies dealing with problems regarding GDP take into account only the interests of traffic control institutions and airlines. The limitation of these works based on the classic CDM model might lead to a limited level of satisfaction among other agents in the CDM process, and, consequently, the results of the process may not be stable [23].

In Brazil, this fact can be verified by the current situation, in which several concessionaires formed by private companies are entering the market to manage the major airports of the country [15]. The project, which aims to improve the quality of services and airport infrastructure, enlarging the supply of air transport to Brazilian population, currently handles billions of *reais* (Brazil's currency) and has duration of 20 to 30 years, depending on the granting rules.

Although the role of the airport operators is of crucial significance, the ATM process currently only accounts for the ATC agency. Airlines and airport managers still do not participate in the decision-making process. Also, it lacks methods to model the association of these partners in A-CDM, as well as the evaluation of distinct objectives between participating private and public companies. In this context, our main contribution is the design of a new model named Deferred Acceptance – CDM (DA-CDM), using the matching approach of Game Theory. This latter approach allows the expansion of the concepts defined in the classic CDM to more general cases. The participation of the decision making with airlines and airport managers is modeled as two-sided markets. By relying on the Deferred Acceptance algorithm [12], a stable output is guaranteed as this algorithm ensures the proper treatment of various goals amongst agents in the process of relocation of slots in a GDP. With the application of the developed algorithm and by comparison to the Compression algorithm, we are able to show satisfactory matching of the flights with the available slots in the A-CDM procedure.

The remainder of the paper is organized as follows. In Section 2 we discuss the related studies on collaborative decision making and matching markets. The slots allocation algorithms based on the classic CDM are presented in section 3. Section 4 describes the proposed DA-CDM model, and section 5 presents the evaluation of our proposal through a comparative analysis of models. We conclude in Section 6 and give suggestions for future work.

2. RELATED WORK

To ensure the safety and flow of flights, ATM deals with the possible inequality between demand for airspace use and capacity of the existing aviation and airport infrastructure [7]. On the other hand, ATM is considered an extremely complex and highly specialized task, besides being strongly based on the experience of the traffic manager. Its activities address critical issues such as efficiency (fluency and delays reduction), equity (working with different airlines), adaptability (treating weather conditions), trust and security (managing airports).

This section presents the related researches concerning the concepts of A-CDM, matching markets and algorithms of Game Theory, and optimization models for slot allocation in airport.

2.1 Collaborative Decision Making

In the 1990s, the philosophy of Collaborative Decision Making (CDM) was considered a new paradigm for the Air Traffic Flow Management (ATFM). It was designed based on the premise that an evolution in the processes of communication and information exchange between Air Traffic Control (ATC) agency and airlines would lead to better decisions in managing aircraft traffic [4]. At the time, the information exchange between Federal Aviation Administration (FAA) and airlines, both participants in the CDM, allowed the formulation of the current processes of Ground Delay Programs (GDP).

Usually, the scheduled flight operations are previously allocated to a takeoff/landing queue, comprising ATC slots. An ATC slot can be seen as a minimum amount of time required for an aircraft to be allowed to perform a takeoff or landing operation on the runway of a controlled airport [14].

The maximum number of aircraft that can land at an airport in a given period is known as the Airport Arrival Rate (AAR). The same analogy can be made in defining the rate of takeoff in an airport as Airport Departure Rate (ADR).

If it is detected that a sector of airspace will be congested at a certain time of the day, the traffic controller must apply appropriate measures, trying to reduce the number of aircraft at the affected location. This reduction is intended to maintain a safe amount of flights operating in the same controlled sector, avoiding congestion.

Although there are various restrictive measures such as ground holding delay, airborne holding delay, miles-in-trail, reroute, slot swapping, among others. For security reasons, preference is given to actions that involve solutions regarding ground holding. It is common sense the assumption that it is safer to change the conditions of flight of an aircraft that is in the ground than in the air [6, 13, 27].

When a ground delay program is applied, the AAR of some airports is reduced. Therefore, the incoming flights that should arrive during the scheduled times of congestion are delayed in their takeoffs. This restrictive measure brings a need of a change in the original slot allocation schedule of flights that will use the runways in these airports.

In this context, the GDP can be understood as a multi-stage process that deals with the management of slots queue allocation in airports impacted by operational capacity constraints. It is based on algorithms and information exchange between agents, being defined and applied by ATC agency with the participation of airlines [27].

2.2 Matching Markets

Game Theory has been used as a mathematical theory for modeling and analysis of the strategies among multiple players by economists, mathematicians, biologists and computer scientists and others to develop the applications with considerable social contribution [16, 26]. In recent years, Game Theory has become the focus of several researches in transportation studies [3, 4, 19, 23].

One of the reasons for the success of this theory is due to the diversity of theoretical and real scenarios that it can be applied. For example, we can mention the study of stock market, the dominance of genes in genetic evolution, regional war conflict, election results, economic markets, among others [4, 16, 25].

In economics, it is used to study the relationship between supply and demand of resources in societies. However, some researchers use it to analyze the behavior of allocation algorithms, enabling the distribution of these resources among agents in specific settings [22].

Since 1950's, Game Theory has been used to solve a wide range of problems, such as hiring processes in the labor market, students' admissions in the universities, network and internet design, organ allocation among patients and donors, among others [10,11, 22].

As the use of runways of an airport can be considered as a limited resource of aeronautical and airport infrastructure, the matching markets models can be associated to ATFM processes considering the demand and capacity of the runway for aircraft. Therefore, the allocation of slots, both for landing or takeoff operations can be modeled as a "market".

Although this association seems intuitive, few studies have so far been presented in ATFM. It is a challenge to exploit the potential of the matching approach for enhancement of Airport Collaborative Decision Making (A-CDM).

2.3 Optimization Models for Slot Allocation

The solution of delaying aircraft at the airport to deal with capacity issues is a complex problem known as Ground Holding Problem (GHP), in which the aircraft will be affected and the delay time assigned to each aircraft.

Although there are several methods proposing numerous solutions, ranging from operation research to multi-agent systems, the Ball et al. [4] and Wolfe et al. [29] researches indicate that there is, for a while now, a trend of using optimization models based on Game Theory to attend the evolution of the A-CDM.

Rassenti et al. [18] developed a combinatorial auction mechanism for airport slots; Ball et al. [4] resumed the study, analysis of objectives and concerns regarding aviation auction problems. And Balakrishnan [3] developed two solutions based on market models using Top Trading Cycle (TTC) and Vickrey-Clarke-Groves (VCG) pricing mechanisms.

These innovative studies showed a significant contrast between the proposal and the techniques that are currently using in ATFM. A process using monetary transfers between airlines, during slot allocation, is considered a significant change in the current paradigm. In order to determine the acceptability of these models, a more detailed analysis of exchange policy is required, as well as taking traffic regulators and other participants in the CDM to have a new perspective of the process.

In their recent work, Cruciol et al. [8] developed reward functions to evaluate the performance related to aircraft on ground and in the air management, ground delay control and complexity analysis of air sectors. Ribeiro and Weigang [19] presented a solution based on Game Theory to management the takeoff sequence of aircraft at airports. The proposed decision support system called Collaborative Departure Management (CoDMAN), was developed under the CDM philosophy.

On the other hand, the matching approach has been applied to ground delay problems which was conceptualized based only on the Top Trading Cycle (TTC) algorithm [24]. This mechanism considering one-sided markets, has been defined as aircraft of airlines oriented models [3, 23].

In the model proposed by Balikrishnan [3], the players were defined as agents by individual aircraft. The author has narrowed the solution to meet specific objectives for each flight, without taking into account the strategic decisions of each airline. More recently, the model proposed by Schummer and Vohra [23] to define the agents as airlines, dealing with slots relocation between their aircraft and expanding the CDM's "ownership" concept. Considering the innovation research, the study discussed one-sided market, in which only the interests of ATC agency and airlines are predicted in its architecture.

3. CDM ALGORITHMS

The ground delay program (GDP) is a process carried out in three steps. Two of these steps are executed by algorithms implemented with different functions, as shown in Figure 1. This process is implemented in partnership between the Federal Aviation Administration (FAA) and airlines according to CDM, where the interests of the parties are fulfilled [6].

In the classic CDM model, ATC agency and airlines are main partners in the collaborative decision making. In this process, the airlines provide trusted, reliable, and up-to-date information to traffic controllers, such that a better outcome of slot allocation can be achieved.

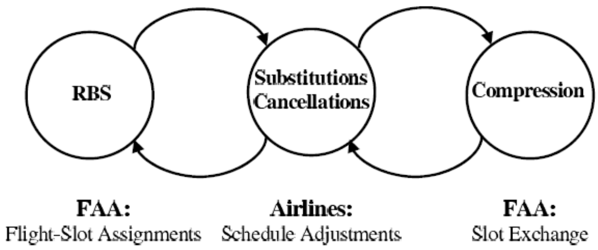

Figure 1: Classic CDM architecture [27].

After the reduction of airport arrival rate (ARR) by a preset time, representing the capacity of the runway configuration in the affected airport, the number of aircraft that will operate at that location is also reduced. Therefore, the first step of classic CDM involving GDP implements the redistribution of slots among the new number of aircraft that can operate per hour at the airport.

The Ration-By-Schedule (RBS) algorithm in Classic CDM intends to create a new schedule for the allocation of slots with revised times, and allocates the flights originally presented based on the new schedule. This allocation preserves the original order of arrival flights and that is defined for each aircraft [27]. Figure 2 shows an example of the application of the RBS algorithm.

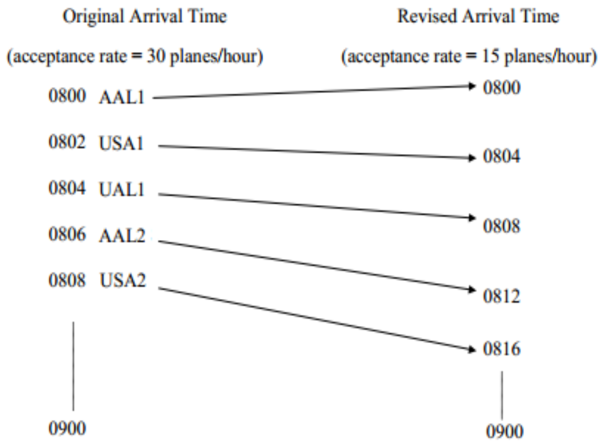

Figure 2: The application of RBS algorithm [6].

It is important to note that the effect of delays on aircraft is cumulative. For example, if the AAR capacity at any airport is reduced from 30 to 15 flights per hour, it will not only result in a 4 minute delay for each aircraft affected by GDP. The first aircraft in the new schedule will not suffer any delay, the second aircraft will use the runway 2 minutes later than in the original schedule, while the third aircraft will operate with a delay of 4 minutes, and so on. Therefore, in the new schedule, the tenth and twentieth aircraft will be assigned a delay of 36 and 76 minutes, respectively, compared to their arrival times as originally planned.

The opportunity thus for airlines to enables the analysis of the results reported by the algorithm, and making strategic decisions in order to mitigate the adverse effects of a GDP on their flight operations. Therefore, in the step named *Substitutions and Cancellations*, it is the airlines' responsibility to communicate on time: a) the possible delays due to mechanical failures and other operational problems, b) the cancellations due to internal adjustments and strategic decisions by airlines on their flights, and c) the replacements of flights among slots "owned" by the same airline, in which a flight can be prioritized over another.

After this second step, the new schedule created by the restrictions imposed by the GDP may contain "holes" due to the cancellations, which might in turn leave slots with no flights assigned to them.

To optimize the process, in which some slots from the current schedule would not be used, an algorithm was created, known as *Compression*, which fills the gaps in vacant slots according to pre-defined rules between ATC agency and the airlines.

The *Compression* algorithm works as follows: when a slot is vacated, the Compression tries to allocate it with another flight from the same airline that "owns" that slot. If the algorithm finds a feasible flight, it performs the exchange, but if there are no flights available, then the algorithm will seek a flight that belongs to another airline. If such a flight is found, the algorithm will allocate it in the slot, also changing the slot "ownership" between the airlines. If no flight is found, the algorithm will simply declare the slot as unused.

The algorithm must handle restrictive slot swapping parameters for a flight to be considered "feasible", such as minimum operating hours and minimum times for arrival at airports [13].

According to [6], this model was built through some basic concepts in CDM philosophy: the concept of "property", by which each airline has total control over its slots, without invading the allocations of competing companies, the concept of "priority", by which flights of the airline that owns the vacant slot are handled first, and the concept of " justice", by which each airline receives a percentage of slots equal to the percentage that it had in the original flight schedule (Official Airline Guide - OAG). More information on this process can be found in [6, 13, 27].

Since its adoption, the Compression algorithm has presented several limitations on the CDM philosophy, regarding its use. According to Schummer and Vohra [23], the algorithm does not guarantee that airlines report, in some cases, their flight cancellations. This situation causes the slots to become unusable, since the competing airlines cannot reallocate their flights to better positions in the schedule. In more serious cases, the algorithm can generate unstable results.

4. DA-CDM MODEL

The model proposed in this paper is based on the allocation mechanism proposed by Gale and Shapley [12], which became known as Deferred Acceptance. The choice of this mechanism is justified by its maturity in solving practical problems in two-sided matching markets, dating from the 1950s, and by its wide usage in complex scenarios that includes from geographical restrictions to compatibility between organ donors [20, 21, 22].

Since the ground delay program (GDP) can be seen as a problem of resource allocation, the environment can be characterized as a "slots market" in which there are two sets, one representing a group of flights and another a group of slots. Dealing with this market by using the DA-CDM model aims to assign each flight to each slot, through a "one-to-one" relationship, respecting the preferences of each allocation, which leads to a stable result.

4.1 Agents Selection

Decision makers in this model have been defined based on key players from “slots market" and studies undertaken by Norin [17] on the ATM stakeholders. In his work, the importance of ATC agencies and airlines as active participants in the CDM philosophy becomes explicit, together with the airport manager in the airport infrastructure, impacted by a ground delay program (GDP). These agents are defined as:

- ATC Agent: is characterized by a single agent responsible for detecting congestion in advance by predicting aircraft occupancy in the air scenario using data available in the flight schedule. Its goal is to control and optimize the traffic flow, applying the security measures at airports when necessary by ATC agency.
- Airline Agents: are agents that have flights that will be operating in a given day. Each agent’s goal is to control its aircraft with regards to planned times of takeoff and landing, reporting possible schedule changes due to technical and/or mechanics operational problems, or cancellations that may interfere in the original flight schedule.
- Airport Agents: are agents represented by the airports of origin and destination, defined in the flight schedule. Their goal is to maintain the appropriate flow of takeoffs and landings in their runways, adapting to the operational capacity restrictions specified by the ATC Agent.

It is important to note that the ATC agent represents a centralizing agent in the market and has no preferences for allocation over any elements in the scenario, due to safety and aircraft traffic flow concerns. In this matter, the Airline and Airport agents can be characterized as decision-makers in the slots allocation problem. They are responsible for determining strategies based on their own goals, in order to enable the correct formulation of the new schedule for airport runways use, in a moment of GDP.

4.2 Reward Structure

Each agent group’s goal in this market may be different and even contradictory. For airlines, it’s important to reduce the total delay of their flights, reducing the costs inherent to these delays, prioritize strategic flights over others, treating differently passengers in international flights or with stopovers, etc. As for the airport's concessionaire, maybe the goal is to optimize the aircraft flow in the apron, to enlarge the rate of passengers’ arrivals, to prioritize flights already en route, among others.

As an initial proposal, a simple approach was defined in order to model the objective function of Airlines agents, according to Equation 1. In this definition, a strategy focuses on the operating profit of each aircraft belonging to a set of flights of a given airline.

$$R_F(f) = \alpha(f)\left[\left(\sum_{k=1}^{q} sr(p_k) - vc(p_k)\right) - fc(f)\right] \quad (1)$$

where *sr* is the sales revenue, *vc* is the variable cost and *fc* is the fixed cost per passenger *p* of flight *f*, for a total of *q* passengers of the same flight. The function α is the importance given to flight *f* by its airline, with a value x, where 0 < x <= 1. This function allows the airlines with the possibility to prioritize some flights over others. Thus, policies have not addressed by Equation 1, because it is still not knew how the destination of the flight, the aircraft size, etc. can be treated. In this configuration, the higher the R_F value, the more profitable is the flight for the airline responsible.

The objective function of the Airport agent is shown in Equation 2 based on a strategy that prioritizes flights according to the amount of passengers and to the aircraft’s delay time. This policy allows the decongestion from inside the airports of origin and the improvement of people flow expected in the destination airport. Moreover, it helps to reduce the stress on crew and passengers of each flight.

$$R_S(f) = \beta(f)\ q^{\theta(t-at(f),\ c)} \quad (2)$$

where *t* represents the current time, *at* is the estimated time of arrival, *q* is the total number of passengers of flight *f* and *c* is an adjustment constant. The β function is the importance given by the airport manager to flight f, with a value x, where $0 < x <= 1$.

The θ function aims to process the result of the difference between the times t and at, in minutes [2, 8]. If the calculation is zero or negative, indicating that the flight is not delayed, the θ function returns the value 1. If the calculation is positive, this value is divided by the adjustment constant c, and the function θ returns the integer portion of the value. For example, if a flight's estimated time of arrival is 09:30 and it's now 11:00, the 90 minutes difference will be divided by c. If c is equal to 30, the function θ returns the value 3. If c is 60, the θ function returns the integer part 1. Therefore, the higher the value of c, the lower is the importance given to the flight delay.

It is important to note that the equations presented allow us to set a priority to flights affected by ground delay program (GDP), enabling an ordering among them.

4.3 Formal Definition

A market of slots with one-to-one relationship is formed by $< F, S, \succ_F, \succ_S >$, where F and S are disjoint and finite sets of allocable elements, where F represents flights $f_1, f_2, \dots, f_m \varepsilon F$ and S represents slots available in the market $s_1, s_2, \dots, s_n \varepsilon S$, containing m e n elements separately.

The elements of the set of arrival slots $S = \{1, 2, 3, \dots, |S|\}$ can be interpreted as ordinal representations of time: for $s, v \varepsilon S$, where $s < v$ means that a slot s represents a time earlier than the slot v.

The earliest possible arrival time (EPAT) for flight $f \varepsilon F$ is denoted by $e_f \varepsilon S$. Therefore, the flight f might be assigned to slot $s_i \varepsilon S$ where $i = 1, \dots, |S|$, only if $e_f \leq s_i$. If the EPAT of a flight f is 10:00am, it will never be able to land in a 09:30 slot at the destination airport.

Each flight f_j, where $j = 1, \dots, |F|$, has a strict, complete, and transitive preference $\succ_F$ over the elements of the other set. The same analogy can be drawn about the preference lists of slots $\succ_S$.

By "complete", it can be understood that all the elements from a set can sort all the elements from the other set in relation to any possible choice, without presenting any indecision in the ordering. By "strict" preference, we mean that the elements of this market should be able to classify each element of the opposite set according to a strict preference order, i.e., without indicating indifference between them. As for "transitive", we understand that there is a consistency in the choices made based on the preferences in a set.

The individual lists containing the ordered preferences can be represented as a set $P(f)$ where $P(f) = s_2 \succ s_1 \succ s_3 \succ \dots \succ s_n$ means that the flight f strictly prefers to be allocated to slot s_2 rather than slot s_1. If the flight f cannot be allocated to slot s_2 so it prefers to be allocated with s_1, and so on.

Allocation preferences are defined by *decision maker agents* using equations 1 and 2, in which airlines are responsible for $\succ_F$ preferences for each of their flights f and the airport affected by GDP is responsible for the $\succ_S$ preferences of each slot s.

A matching is the result of this market, represented by the association of elements from a set with elements from another set through the function $\mu: F \cup S \rightarrow F \cup S$ such that $\mu(f) = s \Leftrightarrow \mu(s) = f$, for all $f \in F$, $s \in S$.

A "blocking pair" is formed by the pair $(f, s) \varepsilon F \times S$ if both prefer each other rather than their pairs formed in the matching μ, i.e., $s \succ_F \mu(f)$ e $f \succ_S \mu(s)$.

A matching is "stable" if it presents a satisfactory allocation for all elements of the sets, where there is no blocking pair.

4.4 DA-CDM Allocation Algorithm

Using Deferred Acceptance algorithm, the allocation algorithm is modeled to run after the substitutions and cancelations step. There are two procedures: pre-processing and main steps.

Algorithm Pre-processing

Input: sets F and S, where:

- F represents the set of flights f, such that $f \in F$, and;
- S represents the set of slots s, such that $s \in S$.

Output: $< F, S, \succ_F, \succ_S >$, where:

- $\succ_F$ represents the set of preferences of each $f \in F$, and;
- $\succ_S$ represents the set of preferences of each $s \in S$.

1: Based on a list of flights F, the airport defines a list of $\succ_S$ preferences for each slot s, guided by strategic premises, according to equation 1;

2: Each airline defines the preferences order for their flights f according to available slots in s. In this model, we use equation 2.

After the formulation of the necessary information for the slot reallocation processes, the main algorithm tries to achieve a result that provides a stable matching, considering the preferences of each element in the market.

Algorithm DA-CDM Allocation

Input: a slot market $< F, S, \succ_F, \succ_S >$, representing a new landing schedule, updated according to the RBS process and the informations regarding delays, cancelations and substitutions from the previous stages.

Output: a new schedule of stable landings μ: $F \cup S$.

1: Each flight $f \in F$ makes an allocation offer to its preferred slot, according to:

a) The feasible arrival time rule, where $s \geq e_f$, and the order in its preference list $\succ_f$.

2: Each slot $s \in S$ accepts its preferred proposal, rejecting all the others, according to:

a) The feasible arrival time rule, where $s \geq e_f$, and the order in its preference list $\succ_s$.

j: Any flight $f \in F$ that is rejected in the step $j-1$ makes a new allocation offer to its next preferred slot $s \in S$ that have not rejected it yet, according to rule 1a. Each slot $s \in S$ remains allocated to its best offer so far, rejecting any other, respecting rule 2a, $j = 1, 2, \dots, m$, $m = |F|$.

Stop: When there are not new proposals to be made:

a) rationalize vacant slots, placing aircraft in better positions, respecting the order already defined and the feasible arrival time rule, where $s \geq e_f$.

b) remaining vacant slots are distributed among the owner airlines, respecting the original order of the algorithm;

c) the algorithm terminates.

With the feasible arrival time rule present in 1a and 2a, the algorithm ensures the correct processing in case of inconsistency in preference lists of flights and slots, represented by the situation where $s < e_f$. It is important to note that the airlines and the airport are responsible for creating these rules, which are defined, in this paper, by Equations 1 and 2.

As e_f is based on the original time of each flight, we have two different scenarios that the algorithm does not need to address: a) the situation where the feasible arrival time of a flight is the last slot in the schedule, because for all flights $f \varepsilon F$, each $e_f < |S|$; b) there is not a situation where two flights have the same arrival slot at the destination airport, because for all flights $f, f' \varepsilon F$, $e_f \neq e_{f'}$.

The algorithm must always follow the ordered preference lists of all allocable elements in the model. According to the "Stop" step, each flight is definitely allocated to the slot it was associated with in the last step of the algorithm, where the result is always a stable matching. The proof of stability and stopping for the allocation mechanism for two-sided matching markets is given by Gale and Shapley [12].

5. COMPARISON AND DISCUSSION

In this section we present the solutions to an analytic example of a ground delay program. The purpose hereof is illustrating the performance of our proposed methodology and to compare the different features of the Classic CDM and DA-CDM models.

After running the Ration-By-Schedule (RBS) algorithm and the Substitutions and Cancellations step (see Figure 1), performed by airlines, suppose the initial scenario of the third step is as shown in Table 1.

Table 1. Initial setting for step 3 of the GDP.

SLOT	Flight	Airline	e_f
s_1	empty	A	
s_2	empty	B	
s_3	f_3	C	1
s_4	f_4	B	1
s_5	f_5	A	2
s_6	f_6	D	5

This example shows four aircraft belonging to the airlines A, B, C and D, respectively, competing for six slots of which two are vacant due to flight cancellation in the previous step, as well as Substitutions and Cancellations. The feasible arrival time of each aircraft is shown in column e_f. This schedule is based on the time originally scheduled for flight f, and represents the restriction that the flight can only get to slot s in the destination airport if $s \geq e_f$.

Based on this information, in a preprocessing step, the algorithm defined in the DA-CDM model creates preference lists where, by Equation 1, airline agents are responsible for the aircraft and, according to the rules defined in Equation 2, the airport agent is responsible for slots preferences. For illustrative purposes only, we hypothetically define the preferences of all allocable elements (flights and slots) as shown in Table 2.

Table 2. Preferências dos voos e SLOTS.

Airline Agent	Airport Agent
	$P(s_1) = \{f_5 \succ f_4 \succ f_3 \succ f_6\}$
$P(f_3) = \{s_1 \succ s_3 \succ s_2 \succ s_4 \succ s_5 \succ s_6\}$	$P(s_2) = \{f_5 \succ f_3 \succ f_4 \succ f_6\}$
$P(f_4) = \{s_1 \succ s_3 \succ s_2 \succ s_4 \succ s_6 \succ s_5\}$	$P(s_3) = \{f_6 \succ f_4 \succ f_3 \succ f_5\}$
$P(f_5) = \{s_3 \succ s_6 \succ s_4 \succ s_1 \succ s_5 \succ s_2\}$	$P(s_4) = \{f_5 \succ f_6 \succ f_3 \succ f_4\}$
$P(f_6) = \{s_4 \succ s_2 \succ s_1 \succ s_3 \succ s_5 \succ s_6\}$	$P(s_5) = \{f_6 \succ f_5 \succ f_3 \succ f_4\}$
	$P(s_6) = \{f_4 \succ f_5 \succ f_6 \succ f_3\}$

At this point, the main processes from Classic CDM and DA-CDM perform as follows:

Compression 1: starts by searching for flights from airline *A* that may be allocated to s_1. The only active flight from airline *A* is f_5, but it cannot be allocated because its feasible arrival time (e_f) is s_2. Therefore, since *A* has no more feasible flights, the flight from the next company that can be assigned to s_1 is f_3 from airline *C*. After performing the swapping, the algorithm also exchanges the slot's ownership between airlines.

DA-CDM 1: flights f_3 and f_4 make allocation proposals to slot s_1, and flight f_5 makes a proposal to s_3, which are, according to the preference lists in Table 2, all their first choices. Flight s_6 would like to propose an association with s_4, but since its e_f is 5, its proposal is directed to s_5, in accordance with the algorithm's first rule. The slot s_1 accepts f_4*'s* proposal, which is its most preferred flight, rejecting flight f_3. The slot s_3 accepts f_5*'s* proposal, those being its only proposals so far, and s_5 accepts flight f_6 under rule 2a.

After the processes' execution, the resulting allocation from the first cycle is shown in Table 3.

Table 3. Compression x DA Algorithm (end of cycle 1).

	CDM			DA-CDM		
SLOT	***Flight***	***Airline***	e_f	***Flight***	***Airline***	e_f
s_1	f_3	C	1	f_4	B	1
s_2	empty	B				
s_3	empty	A		f_5	A	2
s_4	f_4	B	1			
s_5	f_5	A	2	f_6	D	5
s_6	f_6	D	5			

Under this scenario, the processes run again as following step 2:

Compression 2: in this moment, the algorithm verifies that the slot s_2, which is vacant, belongs to airline *B* and its flight f_4 can be moved to s_2, according to his feasible arrival time. Therefore, the algorithm executes the swapping.

Table 4. Compression x DA Algorithm (end of cycle 2).

	CDM			DA-CDM		
SLOT	***Flight***	***Airline***	e_f	***Flight***	***Airline***	e_f
s_1	f_3	C	1	f_4	B	1
s_2	f_4	B	1			
s_3	empty	A		f_3	C	1
s_4	empty	B				
s_5	f_5	A	2	f_6	D	5
s_6	f_6	D	5			

DA-CDM 2: in this new cycle, the flight f_3 makes an allocation proposal to slot s_3, second in the preference list and not yet rejected. Even though s_3 is assigned to f_5, according to its preference list, the slot s_3 prefers to be allocated to f_3 rather than to f_5. Thus, it dispenses with the flight f_5 and gets f_3. Table 4 shows the result of the end of cycle 2.

Now it is possible to verify the execution of the rest processes.

Compression k: the next vacant slot belongs to airline *A* and among its flights that can be allocated to it. The flight f_5 is chosen by the algorithm due to $e_f \leq s_3$. The slot s_4 remains vacant because there are no flights that could be allocated and flight f_6 is allocated to s_5, respecting its feasible arrival time of 5.

DA-CDM k: as the flight f_5 was rejected in the previous cycle, now it makes a proposal to the next slot on its preference list that has not yet rejected it. Therefore, f_5 is allocated to s_6. As there are no more proposals to be made, by the "Stop *a*" step, f_3 can be moved to s_2, and f_5 can be moved to s_3. Since the e_f from flight f_6 is 5, its position cannot be improved. Meanwhile, by the "Stop *b*" step, the vacant slots are distributed among its owner airlines, according to their original order in Table 1.

As the vacant slots cannot be allocated to any more active flight, the algorithms terminate with the schedule presented in Table 5.

Table 5. Compression x DA Algorithm (end of the process).

SLOT	**CDM**			**DA-CDM**		
	Flight	***Airline***	e_f	***Flight***	***Airline***	e_f
s_1	f_3	C	1	f_4	B	1
s_2	f_4	B	1	f_3	C	1
s_3	f_5	A	2	f_5	A	2
s_4	empty	B		empty	A	
s_5	f_6	D	5	f_6	D	5
s_6	empty	A		empty	B	

This hypothetical scenario enables the monitoring of both algorithms operation. It is important to note that, in the DA-CDM model, airlines *B* and *C* were not rewarded or punished in the allocation DA-CDM process. All allocations were made respecting both preferences of airlines on flights, and of the airport on slots. The original order of vacant slots was also remained by the end of the process, enabling a more equitable allocation for airlines. This is important in situations where the algorithm needs to be reprocessed due to dynamic changes in the air scenario.

Based on this example, on the execution of each process, and on the evidence from literature (see Section 3 and 4), the main features of both models can be verified as shown in Table 6.

Table 6. Comparison between Classic CDM and DA-CDM.

Items	**Classic CDM**	**DA-CDM**
Agent ATC	Deals with runway use restrictions, imposed on airports.	To deal with runway use restrictions, imposed on airports.
Agent Airline	Do not have strategic preferences over aircraft allocation.	With the strategic preferences over aircraft allocation.
Agent Airport	Not mentioned.	With the strategic preferences over slots allocation.
Arrival slots	Are filled whenever possible.	To be filled whenever possible.
Property	If an airline cannot use its available slot, it is always compensated with slot "ownership" to exchange with another airline that owns a flight available.	The airlines retain ownership over their vacant slots at the end of the process, ensuring the original order of slots.
Priority	The flights from the airline that owns the vacant slot are considered before the flights of other airlines.	All flights have the same priority in the process.
Justice	At the end of the process, each airline has the same percentage of slots they did at the beginning of the process.	At the end of the process, each airline has the same percentage of slots what they did at the beginning of the process.
Slots loss	There is no possible way an airline loses involuntarily a slot that it owns.	There is no possible way for an airline to lose involuntarily a slot that it owns.
Order of operation	The order by which flights are chosen to operate impacts on the final result of allocation.	The order by which flights are chosen to operate does not impact on the final result of allocation.
Estability	It may produce unstable results.	It always finds a stable result.

As showed in Table 6, both methods have positive and negative aspects. The proposed model solves the slot allocation problem using Game Theory. The algorithm developed in this paper allows one more ATM stakeholder participate of the GDP process enhancing classic CDM concepts. It is important to mention that using Game Theory all agent preferences are respected by the new algorithm.

6. CONCLUSIONS AND FUTURE WORK

We present a Deferred Acceptance CDM model using a matching approach for airport collaborative decision making (A-CDM) with the participation of three agents: ATC agency, airlines and airport managers. As the ground delay program (GDP) is a sophisticated process with dynamic online control property and limited slot resources, the mechanism of two-sided matching markets demonstrates a suitable solution to allocate flight slots in Airport CDM. The proposed model also involves a new player such as the airport managers concerning the restrictive measures in the application of ground delay program.

Comparing to the Compression algorithm in classic CDM, the DA-CDM algorithm aims to assign each flight to each slot, through a "one-to-one" relationship, respecting the preferences of each allocation. This leads to a stable allocation in the case of flight delay(s), as well as in other cases. The main benefits for the partners in CDM and the advantages of the developed model can be summarized as:

- For the ATC agency, the DA-CDM model provides the allocation results by a reliable process including ground delay program (GDP), in which the standards of flow and flight safety are maintained.
- For airlines, the DA-CDM model provides the allocation results for aircrafts by an efficient process directly to reduce the operation cost in taxiing, fuel, crew expenses, and also to reduce the impact to environment.
- For airport managers, the DA-CDM model involves their participation in the decision making process to help the management and optimization of airport resources by improving the fluency of aircrafts on runways, coordination on the apron and the passengers´ movement through gates, among others.
- Even the DA-CDM model does not involve the decision participation of the passengers, the application of the developed model can reduce the delays by applying coordinated actions between airlines and airports achieving a greater proximity of the flights' original departure and arrival times.

Besides allowing the participation of key agents in the ground delay program, DA-CDM model also allows the definition of preferences of airlines and airport managers to allocate a aircraft to a slot that are respected by the Deferred Acceptance algorithm. This is an important feature of the matching mechanism that can be used to create the possibility of defining specific roles for each agent. This advantage is for ATC agency, airlines, and airport managers to develop the local strategies in a global solution.

It is important to note that, in the current A-CDM application, the airport managers are absent in the decision process. In our proposed model, airport managers are included as a decision agent in the A-CDM process. They affect and are affected by GDP involving the processes of takeoff and landing. The airport managers are also responsible for ground handling of aircraft and services for passengers, such as airport operators, aircraft operators, and ground service handlers, among others. This part should be also included in the A-CDM process.

As the future work, the DA-CDM may be modified with the capacity to define the preferences from airport managers such as approach managers (APP), tower, ground, and other managers from various airport services. Further, the analysis of time and complexity on the algorithm could be provided and DA-CDM should be modified with the capacity to get the optimization results via Pareto efficiency. In the application of the DA-CDM, some performed tests should be also considered with the different purposes for each agent. For example, the allocation effects on aircraft can be analyzed in difference scenarios. Attention could also be given to handling the possible coalition between airlines by using real data from the Brazilian Air Navigation Management Center (CGNA).

7. REFERENCES

[1] Agogino A. and K. Tumer. Regulating Air Traffic Flow with Coupled Agents Advances in Complex Systems, In *Proc. of 7th Int. Conference on Autonomous Agents and Multiagent Systems*, 535-542, Estoril, Portugal, 2008.

[2] Arruda Junior, A. C., Weigang, L. and Barros, A. Fairness analysis with flight cost impact using reinforcement learning approach. *Journal of the Brazilian Air Transportation Research Society*, 8, 9-27, 2012.

[3] Balakrishnan, H. Techniques for Reallocating Airport Resources during Adverse Weather. In *Proc. of the IEEE Conference on Decision and Control*, 2949 - 2956, New Orleans, USA, 2007.

[4] Ball, M., Donohue, G., and Hoffman, K. *Auctions for the safe, efficient and equitable allocation of airspace system resources*. In Cramton, P., Y. Shoham and R. Steinberg, eds. *Combinatorial Auctions*, MIT Press, Cambridge, pp 507-538, 2005.

[5] Ball, M. O., Hoffman, R. L. and Mukherjee, A. Ground Delay Program Planning Under Uncertainty Based on the Ration-by-Distance Principle. *Transportation Science*, 44(1):1-14, 2010.

[6] Butler, T. D. *Optimization Model with Fairness Objective for Air Traffic Management.* NEXTOR report, University of Maryland, College Park, MD, 112 p, 1998.

[7] Crespo, A. M. F., Weigang, L., Barros, A. Reinforcement learning agents to tactical air traffic flow management. *International Journal of Aviation Management*, 1(3), 145-161, 2012.

[8] Cruciol, L. B. V. , Arruda Junior, A. C., Weigang, L., Li, L., Crespo, A. F. Reward functions for learning to control in air traffic flow management. *Transportation Research. Part C, Emerging Technologies*, 35, 141-155, 2013.

[9] Dib, M. V. P., L. Weigang, L., A. C. M. A. Melo. 2007, Approach of Balancing of the Negotiation among Agents in Traffic Synchronization. *IEEE Latin America Transactions*, 5, 338-345, 2007.

[10] Ergin, H. and Sönmez, T. Games of School Choice under the Boston Mechanism. Mimeo, MIT. *Journal of Public Economics*, 90, 1-2 (January), 215-237, 2006.

[11] Gai, T., Lebedev, D., Mathieu, F., Montgolfier, F., Reynier, J., and Viennot, L. Acyclic preference systems in P2P networks. In *13th European Conference on Parallel and Distributed Computing*, LNCS 4641, 825-834, 2007.

[12] Gale, D. and Shapley, L. College Admissions and the Stability of Marriage. *American Mathematical Monthly*, January, 69(1), 9-15, 1962.

[13] Hoffman, R. L. *Integer Programming Models for Ground-Holding in Air Traffic Flow Management.* Dissertation, PhD, Department ISR, NEXTOR, 1997.

[14] ICAO. DOC 9854: *Global Air Traffic Management Operational Concept. International Civil Aviation Organization.* DOC 9854-AN/458, 2005.

[15] INFRAERO. *Concessão de Aeroportos.* http://www.infraero.gov.br/index.php/transparencia/concessao.html, 2013.

[16] NOBEL. *Stable matching: Theory, evidence, and practical design.* The Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2012, Alvin E. Roth, Lloyd S. Shapley, Advanced Information, 2012.

[17] Norin, A. *Airport Logistics: Modeling and Optimizing the Turn-Around Process.* Licentiate thesis, monograph, Department of Science and Technology, Linköping University, SE-601 74 Norrköping, Sweden, 2008.

[18] Rassenti, S., Smith, V., and Bulfin, R. *A combinatorial auction mechanism for airport time slot allocation.* Bell Journal of Economics, 13(2), 402-417, 1982.

[19] Ribeiro, V. F. and Weigang, L. Collaborative Decision Making with game theory for slot allocation and departure sequencing in airports. In *17th Air Transport Research Society World Conference*, Bergamo, Italy, 2013.

[20] Roth, A. E. and Peranson, E. The Redesign of the Matching Market for American Physicians: Some Engineering Aspects of Economic Design. *American Economic Review*, 89(4): 748-780, 1999.

[21] Roth, A. and Sotomayor, M. 1990. Two-sided matching: A study in game-theoretic modeling and analysis. *Econometric Society Monograph* 18. Cambridge, Cambridge University Press.

[22] Roth, A. E., Sönmez, T. and Ünver, M. U. Kidney Exchange. *Quarterly Journal of Economics*, 119(2), pp. 457-488, 2004.

[23] Schummer, J. and R. V. Vohra. Assignment of Arrival SLOTS. *American Economic Journal: Microeconomics*, 5(2): 164-85, 2013.

[24] Shapley, L. and Scarf, H. On Cores and Indivisibility. *Journal of Mathematical Economics*, 1, 23-28, 1974.

[25] Sönmez, T. and Ünver, M. U. *Matching, Allocation, and Exchange of Discrete Resources.* Handbook of Social Economics, Vol. 1A. The Netherlands: North-Holland, 781-852 edited by Jess Benhabib, Alberto Bisin, and Matthew Jackson, 2011.

[26] Von Neumann, J. and Morgenstern, O. *Theory of Games and Economic Behavior*. Princeton University Press, 1944.

[27] Vossen, T. and Ball, M. *Optimization and mediated bartering models for ground delay programs.* Naval Research Logistics, 53(1):75-90, 2006.

[28] Weigang, L., Dib, M. V. P., Alves, D. P., Crespo, A. F. Intelligent computing methods in Air Traffic Flow Management. *Transportation Research. Part C, Emerging Technologies*, 18, 781-793, 2010.

[29] Wolfe, S. R., Jarvis, P. A., Enomoto, F. Y., Sierhuis, M., Putten, B., and Sheth, K. S. *A Multi-Agent Simulation of Collaborative Air Traffic Flow Management.* Multi-Agent Systems for Traffic and Transportation Engineering, p. 357-381, edited by Ana L. C. Bazzan and Franziska Klügl, Information Science Reference, 2009.