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Research on the TTC-CDM Algorithm in Collaboration Decision Making of the Airport Slot

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Abstract: With the growing of the globalization, the civil aviation grew in popularity, the air transport industry has witnessed significant growth driven by advancements in science and technology. This progress has also led to the emergence of resource allocation inefficiencies at many airports. Apart from building more runways and airports, lifting the efficiency of existing capacities is a much more cost-effective strategy, where Top Trading Cycle (TTC) algorithm is a prospective solution. This study's application of TTC to the slot allocation problem is different from conventional TTC. Conventional Top Trading Cycle considers preferences of unilateral agents. In this study, there are two different kinds of agents that have their own preferences, airlines with flights and airport managers owning the slots. Therefore, this research's objective is to implement TTC to the slot allocation while respecting preferences of both sides, TTC-CDM algorithm would be useful. This study discussed this algorithm by performing a case study with modelling situation of airport slot allocation in a particular moment. Ultimately, the result of this case study is Pareto efficient.

Keywords: TTC, collaboration decision making, differed acceptance, pareto efficiency

1. Introduction

The first airplane was invented in the United States in the 20th century (a product of the industrial Revolution in the real sense) by the Wright brothers, who made a significant contribution to the world's aircraft development history. Then during the period of 1920s and 1930s, aviation industry developed very fast, which is the so called "Golden Age of Aviation", when the modern aviation industry finally took off after a protracted era [1].

With the growing of the globalization, the civil aviation grew in popularity, the air transport industry has witnessed significant growth driven by advancements in science and technology. This progress has also led to the emergence of resource allocation inefficiencies at many airports. As airports expand their operations, the demand for aircraft increases as well and the airport congestion is becoming a serious problem in many airports in transitory city due to the large number of passengers and flights. The increase of the importance of the air traffic and the shortage in airport capacity or the slots results in congestion at both airports and labor mobility, especially the exist of the airport delaying, the demand requiring the expansion of airport rise significantly. Although the growing demand for the transportation hubs incentivizes the building of new airport, to build a new airport may produce a time leg as it costs effective and requiring time especially in the first-tier city, thus an algorithm that can improve the allocation of airport slots would be helpful and prior to build a new one.

By solving this allocation problem, the passenger mobility will be improved as well as the economic welfare of airport manager by taking the airport manager's and airlines' preferences into account simultaneously, furthermore the congestion problem due to flight delays as well. To act more efficiency, the CDM strategy has been implemented to handle the available air traffic resources [2].

2. Literature Review

2.1. Explaination of Current Problems in Aairport Slot Allocation

Airports in most large cities are faced with congestion problems, and airport administrators choose to find the proper slot allocation results to alleviate this problem. This allocation algorithm not only needs to consider the passenger capacity of the flight but also the problem of the late or early arrival of the plane. However, inefficient allocation often results in unused or misused slots at airports [3].

Although in a congested airport, for example, in a city with a large traffic flow, overall, 10% of the slots in such an airport are still unused or not utilized [4]. This is the data after considering the delay control problem, which can be seen in the airport allocation The problem requires a good allocation algorithm to solve this problem. The case study of specific airports in existing research also supports the existence of such allocation problems. A study on the Greek airport system shows that slot allocation is generally inefficient in the Greek airport system. The authors found that there are optimized allocation schemes at each time to maximize slot usage efficiency and alleviate congestion problems [5].

As for the loss caused by this allocation, the existing research has also given certain quantitative analysis results. According to the report given by Airport Council International 3 Europe (ACIE, 2009), the airport will lose nearly 20 million euros in revenue every quarter because of the invalid allocation of airport slots. The allocation problem has seriously lost the economic benefits of the airport and restricted the mobility of the population [6].

2.2. Comparation between Several Mechanisms

Existing studies have used different allocation algorithms on the airport slot allocation problem, and the results of these allocation algorithms are not the same. This section mainly discusses four allocation algorithms.

The first is the Trading cycle (TC). This allocation algorithm only considers a group of stakeholders when it is in operation. For the airport slot allocation problem, this algorithm can only satisfy airlines and ATC agents, that is, to ensure that it does not cause excessive congestion and satisfy the preference of airlines while ignoring the preference of airport manager [7]. Moreover, this allocation algorithm cannot be manipulated by misreporting the feasible arrival time of its flights and it cannot always obtain stable results either.

The second allocation algorithm is the compression algorithm (CA). This allocation algorithm, with the help of the CDM algorithm, can solve the waiting issue on the ground. This mechanism is the generality of the TTC algorithm studied previously, which can motivate airlines instantly to bring out all the other unavailable slots. However, using this allocation algorithm, the flights cannot be moved to new slots in each round and the inactive flights cannot be removed either [8].

The third allocation algorithm is pay for the slot, which is also a price mechanism. Although the price mechanism maximizes economic gains when there is a absence of market failures, slot allocation clearly cannot use the mechanism correctly because the algorithm cannot reflect the scarcity of slots. For airlines, their demand for slots comes from the actual number of actual flights

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and airlines only pay based on the actual use of slots, a situation that ultimately leads to a large number of unused slots at crowded airports [9].

The fourth allocation algorithm is Bertsekas' Auction algorithm (BA). This allocation algorithm starts with an empty assignment, which means all the flights are not allocated initially. As this algorithm executes an iterative ascending type of auction, the result after allocation is optimal. However, if the BA algorithm takes into account that users are more proactive in price discovery, it requires airlines to be able to account for the costs incurred by allocating the second-best slot. As a matter of fact, for each flight, the bid price was calculated by the airline internally depending both on the current slot values and on its own cost of delay [10].

3. Analysis and Discussion

Since the game theory has widely used in the resource's allocation problem, to use an algorithm to solve the problem of airport congestion has becoming compatible. The airport slots allocation problem is an allocation problem between two sides of agents: airlines (the demanders of slot) and airport manager (the supplier of slots). The algorithm for a double-sided market matching needs a theory considering the benefits of two totally different groups of users. In managing airports slot allocation, the airport slots can be regarded as a limited or restricted resource, at which only one airplane can use each interval at one time.

3.1. Conventional TTC Algorithm

The traditional TTC algorithm only considers one side of agents' preferences when allocating airport slots. Initially, all flights are paired with available slots and any remaining spare slots. Then, the preferences of each flight for different slots are taken into account, with subsequent flights prioritizing their first choice in their preference list. This process creates an arrow graph that forms a cycle to determine the new pairing result and is subsequently removed from consideration. Each flight then points to its next preferred slot until no further cycles can be formed, completing the pairing process. However, this matching algorithm fails to consider the preferences of airport managers regarding different flights.

3.2. Model of Algorithms

3.2.1. TC Algorithm

This algorithm begins by inputting the initial slots and flights, (f, e) as "active".

In terms of Step 1, if there are no empty slots, the algorithm terminates. Otherwise, design a chart as follows. First, a node for every active slot and every active flight can be introduced. Second, the earliest active slot that f can involve to each flight can be drawn from each flight f. Third, a directed edge to the flight that preoccupies can be drawn from each engaged slot. From each empty slot possessed by any airline A, draw a coordinated edge to (A) the most punctual dynamic flight airline A, on the off chance that one exists; (B) the most punctual dynamic flight in F.

Regarding Step 2, cycles in the graph are detected and processed until no more cycles exist.

3.2.2. CA Algorithm

This algorithm begins by inputting both slots current schedule and flights current schedule.

For Step 1, the owner of slot c should be identified, i.e., airline a that owns the canceled or delayed flight fi that was assigned to slot c. Then the slot can be filled following these rules. First, the first flight fi of airline a in the current schedule, which can be placed in position c, should be identified.

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Second, the first flight fi from any other airline that can be assigned to slot c should be identified. Third, if no flights can be allocated to slot c. Go back to step 1 and select the next open slot.

For Step 2, the fi flight slot designation should be substituted, and it is clear that the airline now has an open slot. Next, the slot becomes the current slot, and Step 1 is repeated.

3.2.3. TTC-CDM Algorithm

To succeed in the compression phase, the TTC-CDM model was designed after the replacement and cancellation phase in CDM. There are two algorithms in this model, consisting of a pre-processing process and an allocation process.

A preprocessing process was developed to design flight and slots priority lists by agent, using payment functionality for airline agents and airport management agents. This approach is designed through a strategy that concentrates on the operating profit of each aircraft across all flights of a given airline.

The allocation process algorithm aims to create a stable match, taking into account the preferences of each market participant. The algorithm ensures correct handling in case of inconsistency in the priority order of flights and positions expressed by <f and <s.

The algorithm must always follow the precedence of all assignable elements in the model. Therefore, each flight is explicitly assigned to the location to which it was associated in the last step of the algorithm. The following section describes the TTC algorithm applied in this study.

3.3. Advantages and Disadvantages of the Models

TC algorithm is a data clustering algorithm that aims to group similar data points into clusters based on a predefined distance threshold allowing for varying cluster sizes and shapes. This flexibility can be advantageous in airport slots allocation as it can accommodate different levels of demand and prioritize allocation based on proximity. Meanwhile, TC algorithm can handle large data sets efficiently due to its iterative approach of adding neighboring points to clusters. This scalability is beneficial for airport slots allocation, where there can be a large number of flights to schedule. However, its effectiveness highly depends on the appropriate selection of the threshold distance and finding the right threshold value can be challenging and subjective. If the threshold is too small, meaningful clusters may not be formed, while if it is too large, clusters may become too large and heterogeneous. Besides, the TC algorithm primarily focuses on clustering only based on proximity which may result in suboptimal slot allocations that do not align with desired criteria.

CA algorithm is a type of clustering algorithm s specifically designed for handling categorical, which on one hand can be advantageous for categorizing flights based on various attributes such as airline, destination, aircraft type, or time of day in airport slots allocation. On the other hand, the CA algorithm utilizes a hierarchical agglomerative clustering approach, which can provide insights into the relationship between different categories. This can be useful in identifying patterns, similarities, and differences in airport slots allocation based on categorical attributes. However, differing from TC algorithm, the CA algorithm does not provide flexibility in cluster shapes. This can be limiting if certain categories or attributes do not neatly fit into predefined clusters, leading to suboptimal slot allocations. In addition, the CA algorithm is specifically designed for handling categorical attributes and may not be well-suited for continuous attributes such as flight duration, fuel consumption, or passenger load, which can restrict its effectiveness in airport slots allocation.

TTC-CDM algorithm is a computer vision algorithm used for detecting and tracking moving objects in images or videos. Unlike the TC and CA algorithms, TTC-CDM algorithm is specifically designed for object detection and tracking based on motion analysis.

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The TTC-CDM algorithm considers the motion and trajectory of objects, which can be useful in tracking the movements of aircraft on the airport surface. The TTC-CDM is designed to work in real-time, enabling continuous tracking of objects, which can be beneficial in dynamic airport environments.

3.4. Case Study

The TTC-CDM algorithm intends to effectively distribute flights to available slots considering the preferences of airlines and airport managers. Other algorithms put forward in the previous studies can also be employed to find the optimal allocation of slots and flights, but they only take into consideration the preferences of one of these agents, either the airlines or airport managers.

To demonstrate the differences between these algorithms and the feasibility of the TTC-CDM algorithm presupposed in this study, the paper provides detailed theoretical examples of the applications of these algorithms.

The air movements of arrival of Tancredo International Airport (SBCF) in the city of Belo Horizonte, the state of Minas Gerais in Brazil, is applied in this study. SBCF Airport serves 10.2 million passengers annually, with a large number of different domestic and international flights each day. SBCF Airport has only one runway, and the initial flight schedule is usually adjusted to accommodate arrivals and departures. This feature allows to test the airline's available arrival time of settings. The proposed model will allow airlines to strategically move forward or delay flights while adhering to airport operational restrictions.

The data set presented in Table 1 is from the Civil Aviation National Agency (CANA), the Brazilian Enterprise of Aeronautics (INFRAERO), and the airlines TAP from Portugal and AZUL and GOL airlines from Brazil.

Table 1: Air movements of arrival and information of flights from SBCF airport.

	Flight number	Allocated slot	e_f	Ticket per passenger ($)
F_1	TAP-0101	10:28 PM	1	2100
F_2	AZUL-2557	10:32 PM	2	230
F_3	AZUL-2418	10:35 PM	2	170
F_4	AZUL-2418	10:46 PM	4	160
F_5	GLO-1091	10:49 PM	-	canceled
F_6	GLO-1670	10:55 PM	5	155

This algorithm aims to allocate all flights to available slots, taking into account the earliest possible arrival time and agent preferences. The initial setting for the allocation process is shown in Table 2, which consist of flights preferences $<_f$, slots preferences $<_s$ and the earliest possible arrival time of each flight e_f.

Table 2: Initial scenario (flights schedule) and initial set (preferences).

Initial scenario			Initial set	
Slot	Flight	e_f	Airline	Airport
S_1	F_1	1	$P(F_1)=S_1>S_2>S_3>S_4>S_6>S_5$	$P(S_1)=F_1>F_2>F_3>F_4>F_6$
S_2	F_2	2	$P(F_2)=S_1>S_3>S_2>S_6>S_4>S_5$	$P(S_2)=F_6>F_1>F_3>F_2>F_4$
S_3	F_3	2	$P(F_3)=S_5>S_1>S_2>S_4>S_3>S_6$	$P(S_3)=F_2>F_3>F_4>F_6>F_1$
S_4	F_4	4	$P(F_4)=S_2>S_5>S_3>S_4>S_6>S_1$	$P(S_4)=F_4>F_3>F_6>F_1>F_2$
S_5	cancled	-	-	$P(S_4)=F_4>F_3>F_6>F_1>F_2$
S_6	F_6	5	$P(F_6)=S_4>S_3>S_5>S_6>S_1>S_2$	$P(S_6)=F_4>F_6>F_3>F_1>F_2$

The allocation process starts with the step of offer and acceptance. The specific process is shown in the Figure 1.

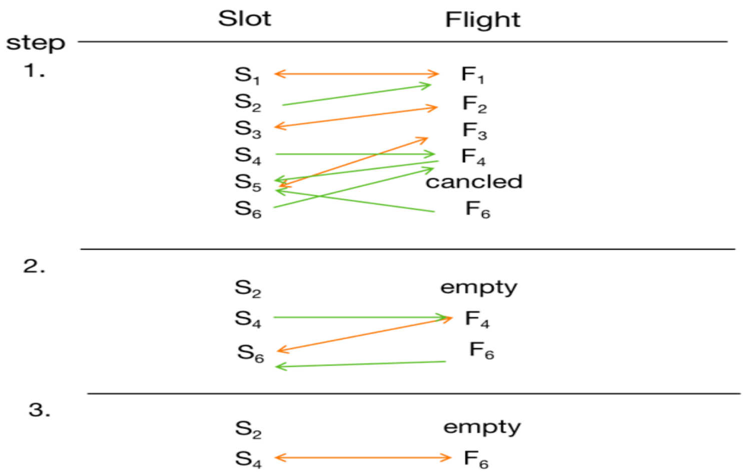

Figure 1: Application of the TTC-CDM algorithm (Photo credit: Original).

3.5. The Result of Pareto Efficiency

From the process of the TTC algorithm in slot allocation, it is not difficult to draw a conclusion that this result is pareto efficient, which can be proved by contradiction. In order to simplify the proof procedure, the paper can first leave out those preferences which cannot be established in the algorithm due to the EPAT (e_f), i.e., turn the preference of Flight 1 P(F_3) into P(F_3).

In this case, the proof procedure can be started as follows. (1) Let μ be the resulting assignment from TTC-CDM in slot allocation. Suppose there is a coalition *B* that deviates profitably by enacting assignment υ; (2) Consider the subset C of slots and flights in *B* who strictly prefer their allocation in υ to that in μ; (3) Let f be a flight who was one of the earliest matched members of C during the execution of the TTC-CDM algorithm; (4) In TTC-CDM, f gets its favorite remaining slots at that step of the algorithm; (5) Since it prefers υ(f) to her TTC-CDM outcome, it must be that υ(f) is originally owned by a flight which leaves the TTC-CDM algorithm at an earlier step; (6) Let the original owner of υ(f) be called f_l who is necessarily in coalition *B* since otherwise f would not achieve that slot through the coalitional move; (7) Say the TTC-CDM cycle where f_l get its match is : $f_l \to s_\alpha \to \cdots \to s_\beta \to f_l$. Remember that $f_l \in B$ and this cycle appeared before the step when a received its match in TTC-CDM. Therefore, f_l has the same match in μ as in υ, and therefore $f_2 \in B$. But then f_2 has the same match in μ as in υ, and therefore $f_3 \in B$; (8) Therefore, this study concludes that $s_\beta \in B$, gets the f_l in this TTC-CDM cycle, and must accept f_l also in υ. This conclusion apparently contradicts with f accepting s_β in υ; (9) The same process of certifying can be implemented from the perspective of slots.

From the dexter process, the paper proved that this slot market assignment would not be blocked by any coalition, which means it is in the core. An allocation is described as being a part of the "core" if no coalition blocks the allocation. A coalition will block an allocation if all members of that coalition can benefit from another allocation. And since there is no blocking, no agent could be in a better situation if the others were not in a worse situation, which means the result is also Pareto efficient.

The result of the algorithm is Pareto efficient, which can be a necessary condition of a thorough operation method. In addition to that, this algorithm fairly considers both sides' preferences, which can be seen as a considerable advance compared with other algorithms, such as, TC algorithm.

Another merit is that this algorithm brings another condition e_f. This condition prominently reduces the possibility of delay because it prevents those preferences which could not be satisfied under objective conditions, and the algorithm will start working with preferences that are objectively rational and achievable.

4. Conclusion

As the conventional TTC algorithm only consider a single preference, which do not safety the collaboration decision making of airport slot. This paper illustrates the application of TTC-CDM algorithm on airport slot allocation problem by considering the two-side preference from both airlines and airport managers. This allows agents to show their preferences simultaneously to form a cycle and an efficient outcome. The proposed market mechanism has several characteristics that make the application of the TTC-CDM algorithm more appropriate.

This study introduces the current slot allocation problems faced by airports through discussing several popular allocation mechanisms, introducing the mechanism of TTC-CDM while providing a full process of it. Finally, discussing the outcome of TTC-CDM and proving that it is Pareto efficient.

All in all, as it considering the earliest possible arrival time e_f, it plays a vital part in solving the problem of airport congestion caused by the cancelation.

Furthermore, this model can apply to a new scenario which considering other conditions that could affect slot allocation. For example, new allocation may take place in airports like London Heathrow and JFK where several runways operate together and result in single slot being allocated to several flights.

It is also possible to consider the slots in departure airports and arrival airports at the same time in order to reach a collaboration between airports. In this way, more diverse situation will also be modeled, which allow the TTC-CDM algorithm to solve more complex and generalized airport slot allocation problems with the growing number of passengers accompanied with the growth of globalization.

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