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The Analysis of Slot Optimization Based on the Top Trading Cycle Method in China Hub Airport

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Abstract: China's aviation industry is facing a scarcer development space. In the absence of means to enhance airport capacity, airport slots have been attached great importance as a scarce resource. Due to the lagging development of China's aviation industry and its detailed fields, slot allocation in China is unscientific, and as a scarce resource, slot utilization in China has much room for improvement. After analyzing the current situation of China's slot allocation system, imperfect laws, regulations and slow marketization process, this paper proposes that the construction of the secondary market can be a substitute for China in the process of exploring the primary market mode, which can be used to significantly improve the utilization and efficiency of slot resources temporarily. This paper introduces in detail the operation method of the Top Trading Cycle (TTC) algorithm and the Top Trading Cycle-Collaborative Decision Making (TTC-CDM) algorithm in the slot allocation secondary market and the short-term potential of solving slot resource shortage, which provides directional guidance for the development space of China's aviation industry.

Keywords: TTC, slot allocation, airport congestion, market design

1. Introduction

The Global civil aviation industry has become one of the sustentacular industries of trade, transportation, and communication between China and the world, and there is still strong demand for development despite the heavy impact of the COVID-19 pandemic. The International Air Transport Association (IATA) predicted that the total number of passenger traffic in the world will reach four billion passenger trips in 2024, which will exceed the pre-COVID-19 level and reach 103% of the total number of passenger trips in 2019 [1]. On top of that, according to a report from the website of the China Central Government in 2020, China has ranked second in the world in terms of passenger traffic by civil aviation for 15 consecutive years, and Guangzhou Baiyun International Airport's passenger throughput reached 43.7681 million in 2020, which ranked first among airports in the world.

Under such circumstances, optimizing aviation resource allocation is a necessary measure to improve the efficiency of air transportation. One of the most straightforward solutions is to build more airports, terminals, and runways. however, considering that these measures may lead to environmental issues and increase pressure on government finances, they will not be consented to and adopted when it is not necessary. Therefore, airport slot as a scarce resource for industry development and airline operations has increasingly become the focus of domestic and international airlines. Although the improvement in slot allocation cannot create added capacity, it is still a much

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more cost-effective and environmentally friendly way for airports to operate scarce capacity more scientifically. In China, the aviation industry started late and the airport slot allocation system development is backward and incomplete.

According to the Aviation Think Tank (ATT) established by the Civil Aviation Administration of China, as the available space for the development of civil aviation continues to shrink, issues like China’s lack of standardized, transparent, and unified airport slot allocation process as well as inefficient slot secondary markets are unfolding. In this case, slots that had been unscientifically allocated are often use less, as it is harder for airlines to make a profit by scheduling flights in this slot, leading to a non-negligible waste of this scarce resource. The allocation efficiency of new airport slots and the service efficiency of existing airport slots at airports need to be further improved. The airport slot allocation and its use, assessment, and withdrawal mechanisms need to be further optimized to improve the utilization of new airport slots and existing airport slots [2]. There is a large optimization space for efficiency in particular with airport slot allocation under limited aviation resources in China’s airline hubs.

2. Management Modes of Airport Slot Allocation

2.1. Two Representative Modes

There are two existing relatively complete airport slot allocation management modes in the world. One is the mixed management mode represented by the United States and Korea which can be seen as the combination of free administrative distribution and paid market transactions. Market and competition can indeed promote the optimal allocation of slots. Such economic forms like auction reflects the value of slots and use leverage adjustment to encourage airlines to refine their operations from their own perspective and maximize the use of their airport slot [3]. In the process of market-based slot allocation, the biggest concern comes from consumers, who worry that airlines will transmit financial pressure to passengers in the end, affecting the overall trend of civil aviation popularization.

The other one is an administrative allocation mechanism based on IATA's "IATA Worldwide Slot Guidelines" (WSG) which has been widely adopted by many parts of the world such as European countries, Australia, Singapore as well as China. This way of distribution is basically dominated by administrative agencies while acknowledging “Grandfather’s Right” (The airline has permanent possession of the slot it has acquired and is effectively using) and allowing one-to-one exchange between airlines if necessary. The administrative distribution mechanism can guarantee the overall interests of the industry and is easier to implement compared to the market allocation mode. "Grandfather's right" in turn ensures the stable development of airline enterprises at the same time. However, purely administrative distribution with the historical priority recognized by the “Grandfather's right” principle is very low in allocative efficiency and cannot accurately reflect the scarcity of slots and the real supply and demand. This principle also impairs the competitiveness of new entrants and benign competition in the air transport market [4, 5].

2.2. Several Issues in China

These downsides which have been demonstrated could be worse in China as China started later in the development, and there are several aspects of the issue that China is confronting.

Basic theoretical research and legislation in China’s airport slot allocation are extremely lacking. This means current management rules are not scientific enough. Even though China has published three regulations in the past two decades, China's slot allocation process is not standardized and transparent enough, and there is a lack of a distribution process recognized by all parties and strictly

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followed. The disclosure of allocation information involved in the process is insufficient, and the transparency and information disclosure of slot management need to be further strengthened [6].

The management mode is based on administrative approval. Although using similar mechanism, European civil aviation authorities do not directly manage the slots, but through the Slot Committee, which guarantees standardization and unity to some extent. However, the Civil Aviation Administration holds the absolute power of distribution in China. Therefore, there are many inconsistencies and uncertainty among regional management agencies in terms of policy provisions, coordination principles, approval standards, and procedures, which causes a lot of inconvenience to airlines in applying for the slots, reduces the efficiency of flight execution, and has a great impact on the use of slot resources [6]. On top of that, the immediate rights and enthusiasm of the slot users are often overlooked. In the context of a lack of transparency, airlines that do not get high-value slots are likely to hold greater complaints about this. Meanwhile, it is easier for state-owned large airlines to occupy a favorable position in the competition for slots.

The marketization process is slow. The 2018 edition of "Civil Aviation Slot Management Measures" clearly points out that the combination of administrative allocation and market allocation is the basic principle of slot management. However, the pilot market reform in Guangzhou Baiyun International Airport and Shanghai Pudong International Airport which had been implemented in 2015 and 2016 wasn’t completely succeeded. One of the reasons is that the extravagant auction prices topped out at nearly 90 million yuan, which is about 12 million dollars. Another reason is that the majority of them were sold by the four largest airlines in China (Air China, China Southern Airlines, China Eastern Airlines, and China Hainan Airlines) and their subsidiaries. This indicated that there is a huge price difference when the two allocation modes coexist, and there is a tendency to form a trading monopoly which benefits the big airlines with deep pockets. Given the above adverse consequences of marketization, the Civil Aviation Administration suspended these relevant pilot projects of marketization in 2017. Since then, there has been no further market-oriented reform of the primary market.

According to the above, the reform and revision of allocation mode in China has a complexity of administrative allocation and still needs a long-term effort. Although the three versions of slot allocation control regulations issued by China since the 21st century (2005 version, 2010 version, 2018 version) have made great progress, there is still a long way to go to reach the completely scientific management level. In the case of the slow development of the primary allocation market, it is a more promising and effective method to make use of the secondary market, boost the enthusiasm of airlines and slot users to let them exchange those acquired slots, so as to achieve the purpose of improving the utilization rate and slots service efficiency from a more micro perspective. The Civil Aviation Administration of China has not made clear the trading rules of the secondary market, which brings great uncertainty to secondary market trading.

Given that most airport slots in China are not obtained by money auctions, it is difficult to accurately price slots traded on the secondary market. In this case, a field of economics, known as “market design”, can give full play to its role. Alvin E. Roth mentioned, “Markets for takeoff and landing slots at airports is one of the areas where market malfunctions are likely and thus adjustments informed by the insights of market design will be called for” [7]. To be specific, the market design presented here is a matching theory for re-assignment where there is an initial ownership [8]. The Top Trading Cycle mechanism is a practical method of market design that is suitable for slot allocations here. This mechanism has been studied deeply in the housing market and can be applied to slot allocation by changing application objects.

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3. David Gale's TTC Algorithm's Application to Slot Allocation

A slot market consists of k slot users and k slots such that slot user i owns the slot h_i, and it has strict preferences $\succsim_i$ over the slots. These preferences must be at least as good as the initial one otherwise the slot user does not need to participate in the exchange.

This study first has a decentralized view of this market with indivisible slots and unit-demand slot users. Given a proposed assignment, if a group of slot users can discover a way of reassigning what they originally own among themselves in a way that makes all of them get a better slot from their own perspective, this study might suspect that they will exercise this opportunity. For Step 1, each slot user points to its first choice slot and each slot points to its initial owner. There exists at least one cycle and no cycles intersect. Assign each slot user in a cycle to the slot it is pointing to. Remove these slot users and slots. For Step 2, each remaining slot user points to its first choice slot among the remaining ones (the proposal of the slot user might be different from the first step as their first choice might have been removed at the first step) and each slot still points to its initial owner. There exists at least one cycle and no cycles intersect. Assign each slot user in a cycle to the slot it is pointing to. Remove these slot users and slots. The process continues until every slot has been redistributed

3.1. Illustration of the Steps of TTC

3.1.1. The Input

The preferences of the 6 slot owners would be counted in advance and be displayed as blue arrows, and the 6 slots would point to Their initial owner using aurantia arrows. The preferences are shown below.

P(F1)=S3>S1>S5>S6>S4>S2

P(F2)=S1>S2>S3>S6>S4>S5

P(F3)=S2>S1>S3>S6>S4>S5

P(F4)=S2>S4>S3>S6>S5>S1

P(F5)=S4>S3>S6>S5>S1>S2

P(F6)=S5>S4>S6>S3>S1>S2

For Step 1, close the cycle: (F1, S3, F3, S2, F2, S1, F1). The slots and flights leave the system, and a new round will be proposed by the remaining slot users(flights) (shown in Figure 1).

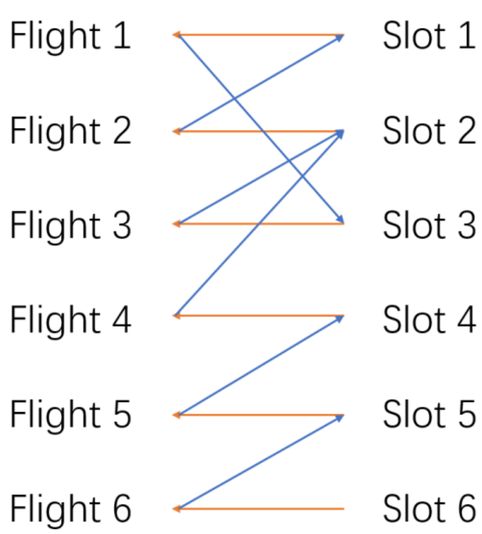

Figure 1: Step 1 for TTC algorithm (Photo credit: Original).

For Step 2, close the cycle: (F4, S4, F4) and (F5, S6, F6, S5, F5). The slots and flights leave the system. Every flight obtains a redistributed result and the simplified process is finished. Therefore, the result would be (F1, S3) (F3, S2) (F2, S1) (F4, S4) (F5, S6) (F6, S5) (shown in Figure 2)

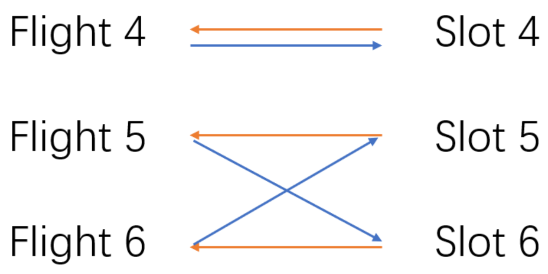

Figure 2: Step 2 for TTC algorithm (Photo credit: Original).

Obviously, the implementation of this algorithm is faster and more convenient than amending laws and regulations and using several years of research and verification to introduce a new system for the primary market of slots. Because in this mechanism, slot owners input their preferences that reflect their actual needs into the algorithm, they can obtain more favorable slots for their development in the output, ensuring the enthusiasm of the airline. After getting slots closer to their needs, airlines will be more proactive in putting them into use steadily. In this way, those slots that have been allocated are less likely to be wasted.

In addition, this algorithm has a qualitative advantage, which is its stability in optimization as well as equity. There is a concept in marketing design called the core. An assignment will be blocked by a single slot user or a coalition (formed by two or more different slot users) if all members in the coalition can get a result that is at least as good as the assigned one, and at least one member in the coalition can get a strictly better result by blocking. An assignment is in the core if it is not blocked by any coalition. It is proved that the TTC algorithm outcome is in the core, thus if a slot user decides to participate in the secondary market exchange, The result obtained must be better than the former one and is already the best result that can be obtained after the overall situation [9]. Although there are some differences in the order of cycle formation, this unbalanced factor can be fixed through random selection to ensure formal fairness. It will not cause dissatisfaction and resistance in slot users.

China has a long-standing administrative mode. TTC algorithm as a centralized and unified distribution method is suitable for management and supervision by administrative departments, particularly for countries like China which has a strong administrative system. The executive branch may establish exchange platforms to facilitate the optimization of allocated slots through scientifically autonomous allocation mechanisms

3.1.2. Proof of TTC Outcome

Let μ be the resulting assignment from TTC. Suppose there is a coalition B that deviates profitably by enacting assignment v.

Consider the subset $\tilde{B}$ of agents in B who strictly prefer their allocation in v to that in μ. Let a be an agent who was one of the earliest matched members of $\tilde{B}$ during the execution of the TTC algorithm. In TTC, a gets her favorite remaining house at that step of the algorithm. Since she prefers $v(a)$ to her TTC outcome, it must be that $v(a)$ is originally owned by an agent who leaves the TTC algorithm at an earlier step.

Let the original owner of $v(a)$ be called b_1 who is necessarily in coalition B since otherwise a would not achieve that house through the coalitional move.

The TTC cycle where b_1 get her match is $b_1 \rightarrow b_2 \rightarrow \cdots \rightarrow b_m \rightarrow b_1$. Remember that $b_1 \in B$ and this cycle appeared before the step when a received her match in the TTC.

Therefore, b_1 has the same match in μ as in v, and therefore $b_2 \in B$. But then b_2 has the same match in μ as in v, and therefore $b_3 \in B$.

Carrying on like this, the paper concludes that $b_m \in B$ gets the original house of b_1 in this TTC cycle, and must get this house also in v. That, of course, contradicts with a getting that house in v.

3.2. TTC-CDM Algorithm

In terms of slot allocation, other algorithms similar to TTC have been studied. One of them is the TTC-CDM algorithm published in the Chinese Journal of Aeronautics, which takes into account the interests of airport parties and airlines and focuses on temporary allocation [10].

To consider the utility of flights and slots fairly, TTC-CDM considers the flight preferences and slots preferences simultaneously. To eliminate the problem of airport congestion due to flight delays, TTC-CDM also set an input e_f which is defined as the *earliest possible arrival time* as well.

The algorithm is designed based on the TTC algorithm, in the first stage of the algorithm, each flight F_i will point to its top choice of slot in the preference list if $e_f \leq s_i$, if the inequality is not valid, it will point to the next slot until satisfy this inequality. At the same time, each slot s_i will point to its top choice of flight in the preference list if $e_f \leq s_i$, if it is not, it will point to the next flight until satisfy this inequality.

In the next step, once there is a cycle (F_i, S_i, F_i), they will be matched with each other, and they will leave the system.

In the k_{th} round of the algorithm, the remaining flights and slots will point to their top choice which is still in the system and satisfies the previously mentioned inequality. The cycle identified will be removed from the system, and the algorithm stops when it cannot form a cycle.

The main difference compared with the TTC algorithm is that the slots no longer point to their initially matched agents but to the top choice in their preference list. There will also be an inequality regarding the e_f.

3.2.1. Inputs

The preferences of airlines are based on a strategy to focus on the operational profit of each aircraft. The preferences of the airport manager (slot) are based on the following rules: first, it wants to reduce flight delay. Secondly, it will prioritize slots according to the number of passengers on board. To be specific, under the condition that the smallest delay is triggered, slots will first prioritize flights with more passengers. Finally, slot allocation wants to reduce the stress on passengers and crew members. This is an extension of the previous two rules because flights with more passengers and delayed flights are tough for both passengers and crew members. Therefore, in order to achieve the previous two rules, the third preference must also be considered.

Most importantly, apart from the preference of flight and slot mentioned above, e_f, a flight's earliest possible arrival time also needed to be considered. It is designed to diminish the congestion problem caused by flight delay, because flights will only propose to the slots that are equal to or later than the e_f, and slots will only propose to flights with the e_f earlier or equal to that slot. In other words, the existence of e_f limits the proposal of flights and slots, but without disturbing the preference.

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3.2.2. Case Study

According to the algorithm operation described above, this study proposes a hypothetical scenario and conducts a case study on it. Table 1 presents the input of the case study, and the procedure of the algorithm is introduced in the “detailed description” and Table 2.

Table 1: Case study initial set.

Initial	scenario		Initial	Set
Slot	Flight	e_f	Airline	Airport
S_1	empty			$P(S1)=F_2>F_3>F_5>F_4$
S_2	F_2	1	$P(F_2)=S_1>S_2>S_3>S_6>S_4>S_5$	$P(S2)=F_5>F_2>F_4>F_3$
S_3	F_3	2	$P(F_3)=S_2>S_1>S_3>S_6>S_4>S_5$	$P(S3)=F_3>F_2>F_4>F_5$
S_4	F_4	3	$P(F_4)=S_2>S_4>S_3>S_6>S_5>S_1$	$P(S4)=F_4>F_2>F_5>F_3$
S_5	F_5	5	$P(F_5)=S_4>S_3>S_5>S_6>S_1>S_2$	$P(S5)=F_3>F_4>F_5>F_2$
S_6	empty			$P(S6)=F_5>F_4>F_3>F_2$

Table 2: Process of TTC-CDM.

	Slot	Flight		Slot	Flight
Step1.	S_1	empty		S_1	F_2
	S_2	F_2	1		
	S_3	F_3	2	S_2	F_3
	S_4	F_4	3		
	S_5	F_5	5	S_3	empty
	S_6				
				S_4	F_4
Step2.	S_2	empty			
	S_3	F_3		S_5	F_5
	S_5	F_5			
	S_6	empty		S_6	
Step3.	S_3	empty			
	S_5	F_2			
	S_6	empty			

For Step 1, arrows are made based on the preferences of flights and slots. (1) Flight F_4 points to slot S_4, as the e_f, the earliest possible arrival time of flight F_4 is 3, which is larger than the top preference of flight F_4, slot S_2, so flight F_4 can only point to S_4 as an alternative. (2) Flight F_5 points to slot S_5, as the e_f, the Earliest Possible Arrival Time of flight F_5 is 5, which is larger than the top preference of flight F_5, slot S_4, and the second preference of flight F_5, slot S_3, so flight F_5 can only point to S_5 as an alternative. (3) Slot S_2 cannot make a proposal to flight due to the feasible arrival time restrictions, hence it points to flight F_2. In the first step, close the cycle: (F_2, S_1, F_2) and (F_4, S_4, F_4). The slots and flights leave the system, and a new round will be proposed by the remaining slots.

For Step 2, close the cycle (F_3, S_2, F_3). The slots and flights leave the system, and a new round will be proposed by the remaining slots.

For Step 3, close the cycle (F_5, S_5, F_5). The slots and flights leave the system, and the simulative algorithm is finished.

Therefore, the final result is (F_2, S_1, F_2), (F_4, S_4, F_4), (F_3, S_2, F_3) and (F_5, S_5, F_5). Since this algorithm originated from the traditional TTC, it is also in the core as well. TTC-CDM algorithm shows a new matching mechanism where two agents including airlines and airport managers and the e_f are considered. This allows agents to show their preferences simultaneously to form a cycle and a profitable outcome. Thus, TTC-CDM algorithms guide both airport managers and airlines to make appropriate decisions and play an important role in solving the problem of airport congestion. Furthermore, as TTC-CDM takes both agents' preferences into account, any disagreements in the allocation of slots can be diminished, which guarantees a "core" outcome for both sides.

4. Limitation

The study demonstrates two similar secondary market transaction methods based on market design to optimize slots allocated to airlines under the administrative allocation system to improve the utilization of slots. However, as a secondary market, its purpose is essentially to make up for the defects of the primary market. This shows that the above method is not the fundamental way to solve slot allocation problems. On the contrary, if relying too much on the secondary market for redistribution adjustment, it will reduce the development process of the primary market and hinder the modernization of the slot allocation system. Moreover, the process of making multiple distributions is inherently inefficient. Secondary markets are still only a temporary solution to the unscientific method of allocation. Only the real modernization of the primary allocation system can fundamentally solve the problem of slot utilization and efficiency. To be specific, it is the management of the legal system and market reform that is eventually needs to be perfected even though it may take a lot of time and effort.

5. Conclusion

This study first analyzed the development and current situation of the aviation industry particularly in China then focused on its airport slot allocation system. The study considered that the allocation of airport slots in China is relatively backward, which has hit the utilization rate of slots and its efficiency as a scarce resource to some extent. The study found that under the circumstance of the slot allocation's slow institutional reform process in China, accelerating the formation and development of the secondary market to expand the use of airport slots in the short term by using the knowledge of market design might be more approachable. This study describes two similar secondary market design methods based on market design, Top Trading Cycle and TTC-CDM. Although the two have different emphases, they both provide ways to improve the utilization rate and efficiency of slot resources without significantly modifying the fundamental system and provide beneficial references for the evolution of slot allocation in China.

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