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Heuristics for the airport slot allocation and trading problem

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Abstract

This work focuses on the slot allocation process, which is one of the research topics in the supply chain and transportation. Effective airport management has become essential due to the rapid growth in air traffic. At airports where coordination is required, slot allocation is largely governed by the IATA Worldwide Slot Guidelines. This process takes place in two main phases as primary and secondary slot allocation. In this work, the primary allocation of slots at many airports is carried out simultaneously through heuristic algorithms with respect to the estimated flight duration. The results show that heuristic algorithms can provide reasonable solutions in a short while. Lastly, trading problems and some alternatives of secondary slot allocation are reported.

Abstrakt

Diese Arbeit konzentriert sich auf den Slot Zuweisungsprozess, der eines der Forschungsthemen des Lieferketten- und des Transportbereichs ist. Aufgrund des raschen Anstiegs des Luftverkehrs ist eine effektive Verwaltung des Flughafens unverzichtbar geworden. An Flughäfen, an denen eine Koordinierung erforderlich ist, wird die Zuweisung von Zeitnischen größtenteils gemäß dem IATA Worldwide Slot Guidelines geregelt. Dieser Prozess erfolgt in zwei Hauptphasen als primäre und sekundäre Slot Zuweisung. In dieser Arbeit wird die primäre Zuweisung von Slots an vielen Flughäfen simultan durch heuristische Algorithmen gemäß der geschätzten Flugdauer durchgeführt. Die Ergebnisse zeigen, dass heuristische Algorithmen in kurzer Zeit vernünftige Lösungen liefern können. Zum Schluss werden Handelsprobleme und einige Alternativen der sekundären Slot-Zuweisung gemeldet.

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1. Introduction

Air transport is an auxiliary factor in ensuring economic growth and development. It also helps trade, encourages tourism and creates employment opportunities. Today, the global economy is becoming more and more connected. Therefore, the number of air passengers is increasing significantly. The International Air Transport Association (IATA) estimates that the number of passengers in 2037 can double -8.2 billion- (IATA, 2019).

Building new capacity at airports, namely the construction of new terminals and runways, is a difficult target due to physical, environmental and political constraints. Therefore, the airline infrastructure should be managed in the best possible manner.

The capacity of an airport is determined by the number of landing and take-off movements that can be defined within a specific time. The airport infrastructure given at certain days and times to perform the landing or take-off operations by the coordinator at the airports is defined by the term slot. In other words, airport capacity is determined by the number of slots used during a limited time. According to IATA Guidelines, airports are categorized into 3 groups for the purpose of airport coordination; Level 1, Level 2 and Level 3 Airports. Level 1 Airports are where airport capacity can meet the demands of the airport users without any coordination. Level 2 is the category defined for airports with congested potential at certain times (weekends, summer seasons, etc.). For example, there are airports in Salzburg and Innsbruck that need to be coordinated during the winter season (De Wit & Burghouwt, 2008). Level 3 airports are airports where airport users need a specific coordinator who implements the Worldwide Slot Guidelines to manage the airport's capacity.

The current procedure for slot allocation in Europe consists of two phases the primary allocation and secondary trading. The primary slot allocation occurs in the IATA Slot conference which is held twice a year for the coordination of Level 2 and Level 3 airports. The slot allocation process is applied according to the published rules and principles of the European Commission. These rules are the evolution of a system created by the International Air Transport Association.

At the highest rate, 58 % of the worldwide airports that need to be coordinated are located in Europe. While airports in Asia represent 21 %, 8 % account for the USA. For North Asia and the Middle East & Africa, these percentages are 7 and 6 respectively (IATA, 2019). Therefore, making the airport slot allocation efficient is an assignment that concerns Europe the most.

Airports, where a coordinator is required, are determined as most congested airports (Level 3). The coordinated airport has its own coordinator who performs multiple tasks. The coordinator determines the airport capacity by fixing the number of available slots per unit of time and applies grandfather rights. In other words, it gives the airlines the right to reuse the slots they used in the previous season. This rule can also be defined as use-it-or-lose-it which will be explained in following section in detail. The coordinator allocates some of the fields that do not cover grandfather rules to new entrances. The tasks so far are called as first slot allocation.

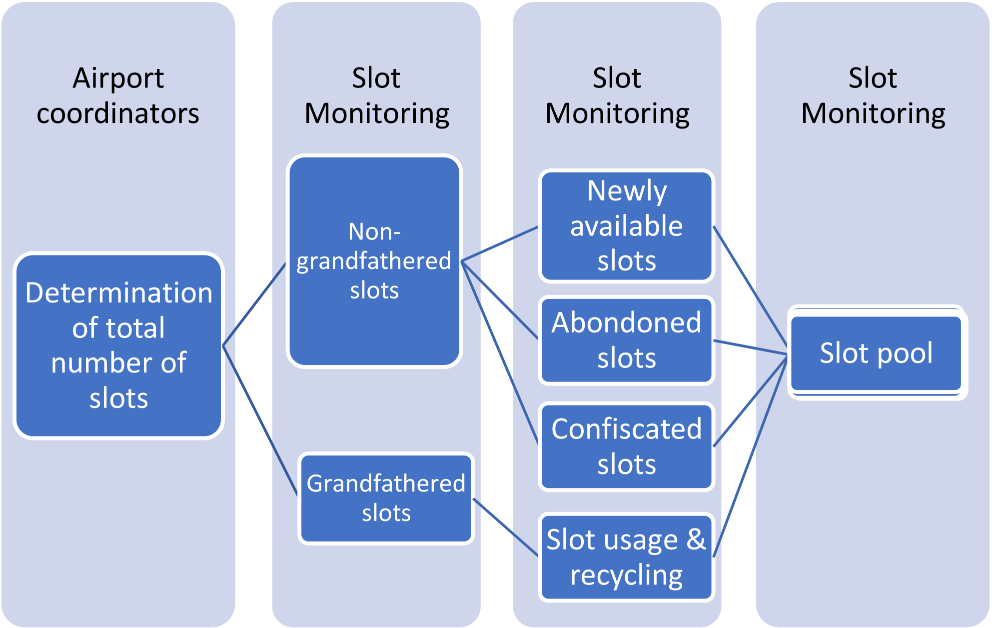

Figure 1: The basic procedure of slot allocation

This phase continues independently for each airport individually. Airport and airline officers then meet at the IATA conference and an agreement is reached. After this conference, the airlines continue to trade through secondary slot allocation which is called bilateral negotiations.

Various studies are included in the literature on the need to allocate slots at the starting and arrival airports of each flight consistently. Some problems may arise in the aforementioned primary allocation and these may be costly to arrange in a secondary allocation. For example, airport coordinators may not be able to arrange collections consistently. Therefore, although some flights have a suitable slot on departure, they may not find a suitable slot for landing even if some slots will stay unused. As Fukui (2010) and Sentance (2003) most studies have been done to maximize the slot capacity utilization and increase competition. Castelli, Pellegrini, & Pesenti (2012) and Pellegrini, Castelli, & Pesenti (2011) have highlighted the importance of the dependency on slots at different airports, respectively, for primary allocation and secondary trade. Pellegrini, Castelli, & Pesenti (2012) extended this approach with a combinatorial exchange mechanism to implement it for bilateral exchange.

This thesis focused on two different metaheuristics developed by Pellegrini, Castelli, & Pesenti (2011), realizing a simultaneous consistent primary allocation at different airports. Considering the airport capacities, the primary slot allocation process is simulated in several airports simultaneously. Unlike Pellegrini, Castelli, & Pesenti (2011), the sector capacity has been ignored. The problem, which is modeled and simulated in Jupyter Notebook, is called simultaneous slot allocation problem capacity (SSAP). Afterwards, the trading problem and some alternative approaches in secondary education will be mentioned.

Figure 2: Air traffic visualization (Patchenik, 2020)

2. Key Principles of Slot Allocation

In this section, the key principles of slot allocation and its effects are reported. Slots at third level airports are allocated by a coordinator who is duly appointed to plan and coordinate limited infrastructure. Airport coordinators can only allocate slots to airlines or aircraft operators. Coordinators should act independently, transparent and fair due to the encourage of air transport market. The airline or aircraft operator must have a slot assigned to it before performing a flight at a third level airport. Humanitarian aid and/or state flights may be exempt from this principle. The slot consists of 5 slots reserved for the same time on the same day of the week. If the slot allocated by the airline is operated by at least 80 %, it has the right to have the same series of slots again for the next season. This rule is called historical priority or grandfather rights. It was first used as a grandfather clause by some states of the USA in the late 19th century to restrict voter registration. Later, this term is used in different fields such as technology, law, sport, etc. This clause claims that the old rule is continuously applied to some existing situations, while the new rule will apply to all future cases. Grandfather rules are the basic and most important principles that are applied almost everywhere in the world.

Airport coordinators share slot usage information online, allowing airlines to track their usage. Airport coordinators are also obliged to warn airlines to take precautions when their use of slots approaches the minimum limit of 80 %. For this reason, airlines are willing to make their slots available to other airlines to avoid losing their slot rights earned from the last season. Slot monitoring consists of two stages, pre- and post-operation analysis. Pre-operation analysis is the process that will support to identify and avoid slot misuse before the operation day. On the other hand, post-operation is going to detect whether the slot is not efficiently used, or the airlines receive the same slots in the next season.

Furthermore, the slot allocation process is easier and airline schedule planning becomes more consistent and stable by means of grandfather rules. Research by Sieg (2010) revealed that grandfather rules and an unrestricted slot ownership plan benefits whereas they reduce profits for airline companies. The negative effects of grandfather rules have also been observed such as causing excessive flights and intensifying the airport congestion, but it has been proved by Sheng, Li, & Fu (2019) that they occur only at airports where the demand / capacity ratio is low (Level 1-2 Airport). Therefore, grandfather rules are implemented only at congested airports (Level 3 Airports). Additionally, grandfather rules can also have other negative effects such as "babysitting" and "slot hoarding" at third level airports.

- Slot hoarding: Airline companies would like to keep the slots because the density in traffic is constantly increasing. They may need slots that are not needed for now because the situation might change in the future. They may also want to keep slots to prevent competitors from being entitled to these slots. It is quite difficult to assess the extent of this effect, because it is difficult to know the importance of a slot for an airline for an outsider. Therefore, slot hoarding can lead to unnecessary traffic and induce airlines to operate with smaller aircrafts (Lenoir, 2016).

- Babysitting: Slots can be transferred to non-competitors within the alliance. Babysitting can also lead to airlines operations with smaller airplanes or to the usage larger planes for low load factors (Lenoir, 2016).

5.1 Primary - secondary allocation

In order to carry out the planned operations at the coordinated airports, all airlines must acquire airport slots. Coordinators allocate slots for airlines operations in a two-step process. As a first step, most airport slots are assigned during primary allocation, based on the IATA World Slot Guidelines. All over the world, this process addresses the allocation of slots, slot turns and slot adjustments (Ranieri, Alsina, Bolic, Castelli, & Herranz, 2014). In the primary allocation, there are some priorities that decision makers in IATA conference must comply with. According to the IATA guidelines, each request is categorized into three different priorities: firstly requests with grandfather rights, secondly requests with new entry status, and lastly all other requests (IATA, 2019). After the coordinator allocates the historical slots, he or she creates a slot pool including newly created slots. Later, the coordinator will categorize it as new participation requests and non-new participation requests for the primary allocation. He or she should allocate 50 percent of the slots in this pool to requests of the companies that are new to the market. He or she should then allocate other slots in the slot pool to requests of the companies, existing in the market.

Only airline companies are appropriate for the new participation. New participating airlines may request a new meeting of Coordination Committee to solve the problem if their slot request is not satisfactorily answered by the airline coordinators (IATA, 2019). Other principles of coordinators for the primary allocations are taking precedence requests on the waiting list over current requests and meeting needs of traveling public and working carriers as far as possible.

In the second stage, airlines try to obtain suitable slots with the approval of airport coordinators for reasons such as changing customer demands, weather conditions, political situations etc. This stage is implemented individually by the following different procedures. Slot exchange without monetary compensation, slot transfers, slot exchange with monetary compensation, and slot buy-sell (where it is permitted) are some possible alternatives. The second stage is also important for the whole slot allocation process because it affects grandfather rules which is the main rule of slot management (Ranieri, Alsina, Bolic, Castelli, & Herranz, 2014). The second allocation allows the airlines to consolidate their programs and keep the slots they had in the previous season for the next season. Airline companies wish to keep the slots as functional as possible, as they do not want to lose the slots allocated to them by grandfather rules. The IATA slot guidelines also include some principles related to holding and returning slots. Airlines may hold the slots only to operate, swap or transfer them. In order to use the limited capacity efficiently at the airport, airlines must immediately return the slots they plan not to operate. Even if it is only for a short time, the returned slots can be allocated to other operators. Lists of returned slot series after Series Return Deadline should be published by the coordinator.

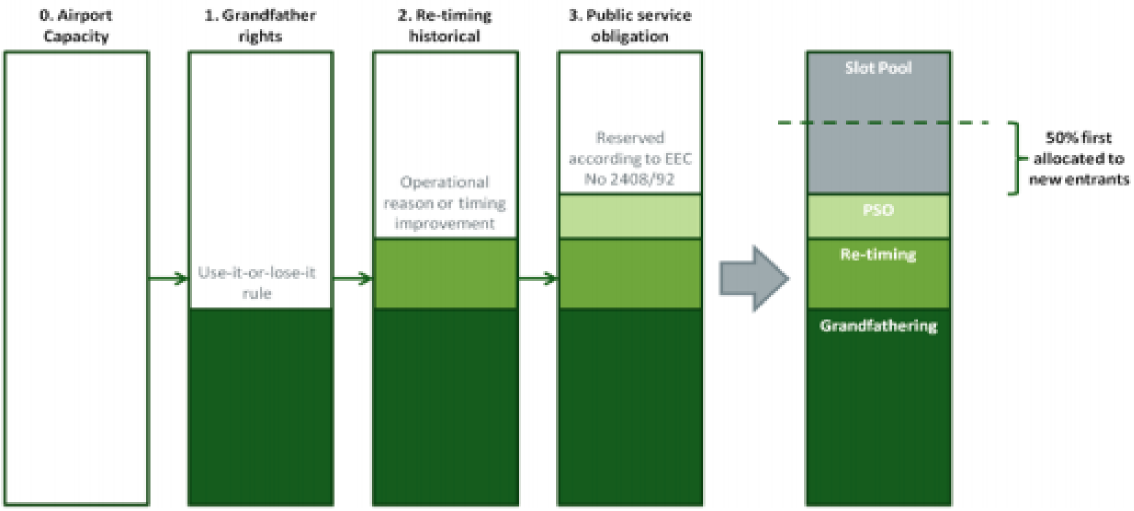

Figure 3: Process of Slot Allocation (Ranieri, Alsina, Bolic, Castelli, & Herranz, 2014)

3. The simultaneous slot allocation problem (SSAP)

SSAP consists of assigning airlines' flight requests to the airport slots. If more than one equivalent solution is reached with the number of flights, it prefers the minimum cost solution (Pellegrini, Castelli, & Pesenti, 2011). The shift cost occurs when a different slot than a requested one is assigned to a flight. The factors affecting this cost may be unsold passenger tickets and additional organizational costs. The SSAP must meet a few requirements such as:

- slot capacity requirements of airports
- time requirements between two airports

In the simultaneous slot allocation problem, the capacity of the "congested" Level 3 airports was taken into account.

The first task of SSAP is to find a feasible solution considering the capacity constraints. Then it has two goals that are hierarchically structured. The first of them is to increase the number of flights to which slots are allocated. The second one is to reduce the cost due to delays.

Iterated Local Search (ILS) (Lourenço, Martin, & Stützle, 2003) and Variable Neighborhood Search (VNS) (Hansen & Mladenović, 2001) algorithms are implemented to provide reasonable solutions for SSAP. The working principle of meta heuristic algorithms is shown in the graph.

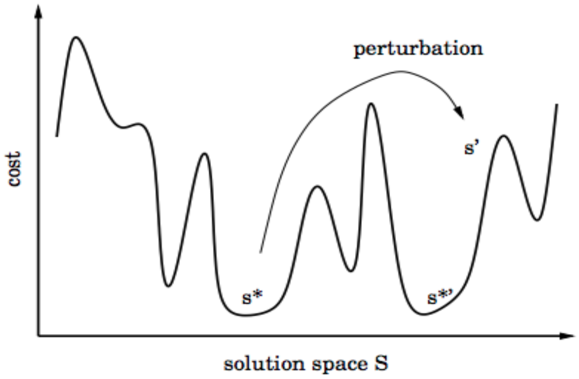

Figure 4: Working principle of metaheuristic algorithms (Lourenço, Martin, & Stützle, 2003)

3.1 The Model

In the algorithms which are going to be presented in this thesis, the time horizon is created by the time intervals of fix length. All slots at airports have the duration of one-time interval, being T the set of time intervals. K represents the set of coordinated airports. From a mathematical point of view, each slot [j, t] with $j \in K$ and $t \in T$ is a pair.

Let A be the set of airlines who requesting flights in slot allocation model. All flight requests are illustrated by F. The capacity of an airport $j \in K$ at the time interval $t \in T$ is $K_{j,t}$.

The ideal departure and arrival time of flight $f \in F$ are dt_f and at_f, respectively. The origin airport of flight $f \in F$ as $orig_f$ and the destination airport of flight $f \in F$ as $dest_f$ are displayed. Furthermore, the acceptable departure and arrival time intervals of flight $f \in F$ to the scheduled airports notations are T_{fdestf} and T_{forigf}. Lastly parameter c_f is used to illustrate the cost of delaying a flight one time interval forward or backward. In addition, a large constant is used in the equation to specify the primary goal in algorithms mathematically. All notations are summarized in Table 1.

F	Set of flights
$K_{j,t}$	The capacity of airport j $\in K$ at the time interval $t \in T$
dt_f	Ideal departure time interval of flight f
at_f	Ideal arriving time interval of flight f
$orig_f$	Scheduled origin airport of flight f
$dest_f$	Scheduled destination airport of flight f
T_{forigf}	Acceptable timeframe for the departure flight f
T_{fdestf}	Acceptable timeframe for the arrival flight f
c_f	The cost of delaying a flight one-time interval forward or backward
C^f	The total cost of delayed flights
M	A large constant

Table 1: Input sets and parameters

3.1.1. Decision Variables

Following binary decision variable is considered for all flights $f \in F$ and all slots $[j, t] \in KxT$:

$$w_{fj,t} = \begin{cases} 1 \text{ if a slot } [j, t'] \text{ with } t' \leq t \text{ is allocated to flight } f, \\ 0 \text{ otherwise.} \end{cases} \quad (1)$$

3.1.2. Constraints

The model includes the following constraints:

$$w^{f}_{orig_f, T^f_{orig_f}-1} = 0 \qquad \forall f \in F \qquad (2)$$

$$w^{f}_{dest_f, T^f_{dest_f}} - w^{f}_{dest_f, T^f_{dest_f}+1} = 0 \qquad \forall f \in F \qquad (3)$$

$$\sum_{f \in F: dest_f = j \vee orig_f = j} w^{f}_{j,t} - w^{f}_{j,t-1} \leq K_{j,t} \qquad \forall j \in K, t \in T \qquad (4)$$

$$w^{f}_{orig_f, t} - w^{f}_{dest_f, t+end_f} \leq 0 \qquad \forall f \in F, t \in T \qquad (5)$$

Constraints (2) and (3) ensure that the time requirement in flight information is observed, and no flight is accommodated to slots outside the acceptable timeframe. The Constraint (4) impose the respect airport capacity requirement. Lastly, Constraint (5) guarantees the duration requirements of flights.

3.1.3. Objective Function

The goal of the model consists of two components: the number of flights accommodated and the cost due to flight delays. The objective function is as follows:

$$z^{*} = \max \textstyle\sum_{f \in F} M * w^{f}_{dest_f, T^f_{dest_f}} - C_f \qquad (6)$$

4. Metaheuristic algorithms

This section contains the definition of two metaheuristic algorithms based on Iterated Local Search (Castelli, Pellegrini, & Pesenti, 2012) and Variable Neighborhood Search (Hansen & Mladenović, 2001) for SSAP. These two algorithms take the landing and departure information, delay cost and time interval of the requested flight as input.

Both algorithms use two local search procedures. The first local search, called flight local search, focuses on increasing the number of flights accommodated. The second local search, called cost local search, tries to reduce the cost of the solution which is offered. Both algorithms reiterate as soon as they find a better solution. The performance of these procedures depends on the number of unsuccessful attempts and the number of flights that will be shifted or not assigned.

```
S = initial solution
trial = 0
while (trial < t & time left) do
    S’ = S after de-accommodating q randomly drawn flights
    for (f in the set of flights non-accommodated in S’, considering in random order) do
        if (capacity in f’s ideal slot at airport is available) then
            accommodate f
            next f
        else
            Comp$_{forig- dest}$ = set of the flights competing with f in orig$_f$ or dest$_f$
                for (f’ in Comp$_{forig- dest}$, considering random order) do
                        randomly shift f’
                        if (capacity in f’s ideal slot at airport is available) then
                            accommodated f
                            next f
    if (number of flights S’ > number of flights in S) then
        S = S’
        if (all the flights are accommodated in S) cost-local-search(S)
        else flight-local-search(S)
    trial = trial + 1
return S
```

Figure 5: Pseudocode of the flight-local-search procedure

(Pellegrini, Castelli, & Pesenti, 2011)

Iterated Local Search and Variable Neighborhood Search algorithms produce random solutions at certain time intervals. For this reason, the flights are ordered randomly all the time and starting from the first flight, they are assigned individually as long as airport capacities allow.

• 5.1 Iterated Local Search (ILS) Algorithm

The ILS Algorithm runs two local search procedures, starting with the randomly generated solution which has been previously mentioned. Then it expands the solution area by calling two local search procedures in a row. The algorithm runs local search procedures multiple times before finishing the investigation of the current region. It updates the solution all the time when it finds a better one. It disrupts the solution after a certain repetition. Thus, perturbation helps the solution to escape from the local minimum. When these two procedures cannot find a better solution, when plugged in to a local minimum, the algorithm starts again with a new randomly generated solution. Based on this algorithm, the best local optimum is assumed to be close to the global optimal (Fonlupt, Robilliard, Preux, & Talbi, 1999). ILS contains three different important parameters: the number of iterations repeated without improvement in the number of flights performed; repeated local search procedures and the perturbation size before any distortion occurs.

```
S = initial solution
trial = 0
while (trial < t & time left) do
    S’ = S after randomly shifting q randomly drawn flights
    for (f in the set of flights accommodated in S’, considering random order) do
        if ($C_f > 0$) then
            $Comp_f$ = set of flights f’ such that $C_{f'} < C_f$, competing with f $orig_f$ or $dest_f$
            for (f’ in $Comp_f$, considering random order) do
                randomly shift f’
                if (f can be shifted) then
                    shift f so that its cost is decreased
                    next f
    if (cost of flights in S’ > cost of flights in S)
        S = S’
        cost-local-search(S)
    trial = trial + 1
return S
```

Figure 6: Pseudocode of the cost-local-search procedure

(Pellegrini, Castelli, & Pesenti, 2011)

```
S = ∅
for (f in the set of all flights, considered random order) do
    if (capacity of f's ideal slot at airport is available) then
        accommodate f
next f
return S
```

Figure 7: Pseudocode for generating random solution

(Pellegrini, Castelli, & Pesenti, 2011)

5.2 Variable Neighborhood Search (VNS) Algorithm

The VNS algorithm also uses two local searches, starting with a randomly generated feasible solution. In contrast to ILS, VNS tries to escape from local optima by increasing the size of perturbation in local searches. When local search procedures fail to improve the current solution in a given repetition, the algorithm continues to search for global optimality with the new randomly generated solution, by setting the perturbation size back to its initial value. The essence of the algorithm is to scan global optimality extensively in the current region before moving to a different region. It has parameters such as the number of repetitions without improving the number of accommodated flights and the number of local search procedures to be performed before increasing / decreasing the size of the neighborhood being searched. The last-mentioned parameter determines the search region by shifting flights randomly in the cost-local search procedure and by assigning flights as non-accommodated in the flight-local search procedure.

```
S* = S = Randomly drawn solution
while (time left) do
    if (no improvement in the last r iterations & not all flights are accommodated) then
        S = randomly drawn solution
    if (not all the flights are accommodated) then
        for (round in 1: k) S = flight-local-search(S)
        if assigned flight requests rate is bigger than 0.99-0.98-0.975
            S = cost-local-search(S)
    else
        for (round in 1: k) S = cost-local-search(S)
    if S is better than S* then S* = S
return S*
```

Figure 8: Pseudocode of ILS Algorithm

(Pellegrini, Castelli, & Pesenti, 2011)

```
S* = S = Randomly drawn solution
$q_0$ = q
while (time left) do
    if (no improvement in the last r iterations & not all flights are accommodated) then
        S = randomly drawn solution
        q = $q_0$
    q = q + i
    if (not all the flights are accommodated) then
        for (round in 1: k) S = flight-local-search(S)
        if assigned flight requests rate is bigger than 0.99-0.98-0.975
            S = cost-local-search(S)
    else
        for (round in 1: k) S = cost-local-search(S)
    if S is better than S* then S* = S
return S*
```

Figure 9: Pseudocode of VNS Algorithm

(Pellegrini, Castelli, & Pesenti, 2011)

In addition to ILS and VNS algorithm pseudocodes, which were written by Pellegrini, Castelli, & Pesenti (2012), lines written in bold letter are added. Because of the randomly generated data, algorithms are not always able to assign all flights to slots in a reasonable time and the cost local search function does not work. With pseudocode, which is written bold, after more than 99 % of the flight requests for small instances, 98 % of the flight requests for medium instances and 97.5 % of the flight requests for large instances are accommodated to the slots, the cost local search function is called.

5. Experimental Setup

ILS and VNS algorithm comparison were done with randomly generated examples. In these examples, the hub-and-spoke structure was used. All flights take-off or land at a hub airport. Limited slot capacity was determined for hub airports. Maximum (forward and backward) shifting of three-time intervals for each flight was allowed. If the slot capacity at the designated hub airport is full up to three units before and after the departure or landing, the flight cannot be shifted.

The number of flights for each sample was determined as a constant percentage (85%) of the total slot capacity of hub airports available. Thus, random samples were produced that would not cause congestion. Randomly generated flight request information is shown as an example in Table 1.

Flight	$orig_f$	dt_f	$\bar{T}_{orig}, \underline{T}_{orig}$	$dest_f$	at_f	$\bar{T}_{dest}, \underline{T}_{dest}$	c_f
0	Lyon	7	(4,10)	Amsterdam	9	(6,12)	20
1	Munich	4	(1,7)	Paris	6	(3,9)	29
2	Liverpool	3	(0,6)	London	5	(2,8)	21

Table 2: Flight request information

The parameters dt and at represent departure time and arriving time, respectively. T_{orig} and T_{dest} parameters show the maximum delay values of departure and arrival times.

The start and arrival airports were identified using Python's Random module, provided that the following conditions were met for each flight: one of them should be the hub, the distance between the two airports should be two-time intervals. As shown in the table, each slot capacity at hub airports was set up randomly according to uniform distributions. The parameters of the cost coefficient were determined as follows: c_f between 20 and 30 randomly. Suggestions will be mentioned in the delay cost coefficient section to determine the parameter defined as a time interval delay cost of the requested flight. The result comparisons of the algorithms were made with three different sample sets listed in Table 1.

	Small	**Medium**	**Large**
Number of hubs	**3**	**5**	**8**
Number of spokes	**17**	**15**	**22**
Number of time intervals	**18**	**18**	**18**
Hub capacity	**[12,16]**	**[12,16]**	**[12,16]**
Number of flights	**~643**	**~1071**	**~1714**

Table 3: Set of instances

The increasing number of hub and spoke airports cause a rise in the number of flights expected from ~643 to ~1714. Because the expected slot capacity at hub airports is 756 on the small instance, 1260 on the middle instance and 2016 on the instance scale. Naturally, the number of flights has been increased at the same rate.

All experiments were implemented in Python 3.7 and conducted on a 2.5 GHz Intel Core i5 with 8 GB installed RAM. To record the accommodated and non-accommodated flights the Python library *Pandas* and to random selections the Python library *Random* was used.

A calculation timeout of 600, 1200 and 3600 seconds has been introduced for the slot allocation metaheuristic algorithms of three different sample sizes with bold lines in pseudocode. Different parameter values were tested with a small sample to find the best parameter values for algorithms.

Parameters	Tested Values
t	**1, 10, 100**
q-cost	**1,5,10,20**
q-flight	**10, 20, 40, 60**
r	**1, 3, 5, 10**
k	**1, 3, 7, 20**
i	**5, 10, 25, 50**

Table 4: Tested settings

6. Experimental Results

In this section, the performance comparison of ILS and VNS algorithms is reviewed. The comparison of each example is based on three benchmarks:

1. the percentage of successfully accommodated flight requests over the total number of flights in the sample. As it is mentioned before, this is the primary goal of both algorithms.
2. algorithms' timeline in slot allocation. More precisely, it is clearly illustrated that what percentage is reached by algorithms during a particular time period.
3. The success performance of the cost local search function that algorithms run after all flight requests have been accommodated or exceeds certain percentage (0.99, 0.98, 0.987) success rate.

The different parameter values as shown in Table 2, were tested. As a result, the algorithms showed high performance with the underlined values. Then, ILS and VNS algorithms were run with medium and large-scale samples to determine the best performing values for both of them because the algorithm performances in the small sample were very close to each other. The parameter values that the algorithms reach the most efficient results with, are shown in Table 3.

The following conclusions were obtained as a result of experiments in the small sample with 600-minute tests with different parameter values. The parameter t, which indicates the number of trials in the flight local search and cost local search functions, gave the best values in algorithms when it was equal to 10 and 100. The parameter q, which is the perturbation value that helps the algorithms to escape from the local optimum, provide results close to each other by showing high efficiency at the values of 20 and 40. The perturbation value resets the number of randomly selected accommodated flights in the flight local search to the non-accommodated one. The parameter q in the cost local search, on the other hand, shifts the randomly determined flights to the extent allowed by the slot capacity. The parameter r is the value that limits the repetition of the algorithms and emphasizes the 3 and 5 values in the trials. The result of parameter k, which is the number of repetitions of the local search functions included in the algorithms, illustrated that the test continues in the medium-large instance with values of 3 and

7. Lastly, the parameter i, which is present only in VNS algorithm and increases the perturbation size, values numbers of 10 and 25 that makes make the algorithm more efficient.

Then, considering that the values of these parameters in these algorithms are affected by each other, $2^5 = 32$ different scenarios covering all values were tested with a 5000-seconds time constraint in the medium-sized sample. The rate of placement of flight requests, which are the primary target of the algorithms, and the average delay cost are shown in the table.

The rate of the flights allocated to the slots at the 3rd level airports successfully is shown in the first line of Table 3 while the second line is for the solution cost. When the first eight scenarios are examined: the ratio has the highest values in the 4th and 5th scenarios.

Scenario 1		**Scenario 2**		**Scenario 3**		**Scenario 4**	
ILS	VNS	ILS	VNS	ILS	VNS	ILS	VNS
0.987	0.989	0.987	0.989	0.983	0.990	**0.989**	**0.990**
Scenario 5		Scenario 6		Scenario 7		Scenario 8	
ILS	**VNS**	ILS	VNS	ILS	VNS	ILS	VNS
0.988	**0.990**	0.985	0.988	0.983	0.986	0.986	0.987

Table 5: Sample parameter setting study

Another conclusion reached during the trials is that the perturbation values of 10 and above affect the cost local search unfavorably. As the perturbation value increases, cost local search function is not able to find cheaper solutions in reasonable time. On the other hand, for flight local search, this value shows efficiency between 20 and 40. Therefore, by making a slight change in these algorithms written by Pellegrini, Castelli, & Pesenti (2012), instead of a single perturbation parameter, two separate perturbation parameters were used in local searches. Thus, while the perturbation value q-flight in flight local search is around 20-40, the perturbation value q-cost in cost local search is around 5.

The 32 scenarios were examined one by one, in the same manner as 8 previous scenarios were examined in order to specify the parameters with the best results of the VNS and ILS algorithms. The best values of algorithms are selected as follows:

	ILS	**VNS**
• Number of trials: (t)	100	10
• Perturbation size of flight-local-search: (q-flight)	40	40
• Perturbation size of cost-local-search: (q-cost)	5	5
• No improvement iterations limit in ILS-VNS: (r)	3	5
• Local search repetition: (k)	7	3
• Increase in perturbation value: (i)		10

The results of the experimental analysis are shown as follows: average accommodated flight demand in percentage (%Flight) and cost savings which is calculated as follows:

$$cost\ savings = \frac{initial\ cost - final\ cost}{initial\ cost}$$

The cost savings of the algorithm are calculated as follows: first, the total delay cost is calculated, either after the flight local search percentage's limit is exceeded or after the flight local search function is completed. Then, the cost is subtracted from the total delay cost which is reached as a result of the cost local search function. This value is then divided by the first calculated total delay cost.

		% Flight	**Cost Savings**
Small	**ILS**	**99**	**0.02**
	VNS	**99.4**	**0.06**
Medium	**ILS**	**98.3**	**0.05**
	VNS	**99**	**0.02**
Large	**ILS**	**97.5**	**0.07**
	VNS	**98.2**	**0.02**

Table 6: Average successful slot allocation rate of algorithms and their cost savings

The ratio of the accommodated flights in the slots to the total number of flights is shown below in the time graph. As seen in the graph, the VNS algorithm reaches high rates in a shorter time than the ILS algorithm. However, the VNS algorithm cannot achieve better results for a long time after a certain rate. The ILS algorithm continues to reach better solutions during this period.

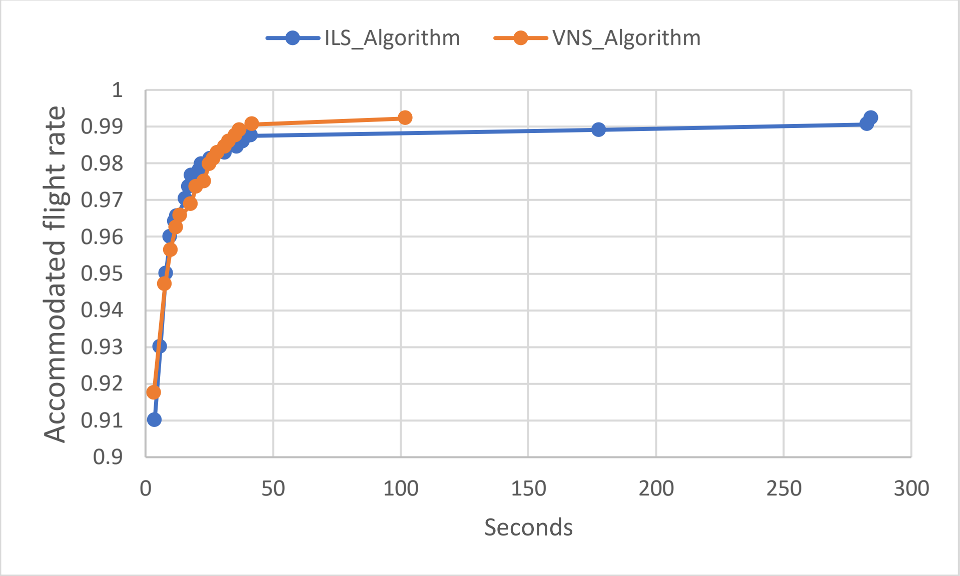

Figure 10: ILS and VNS Algorithms on small size instances

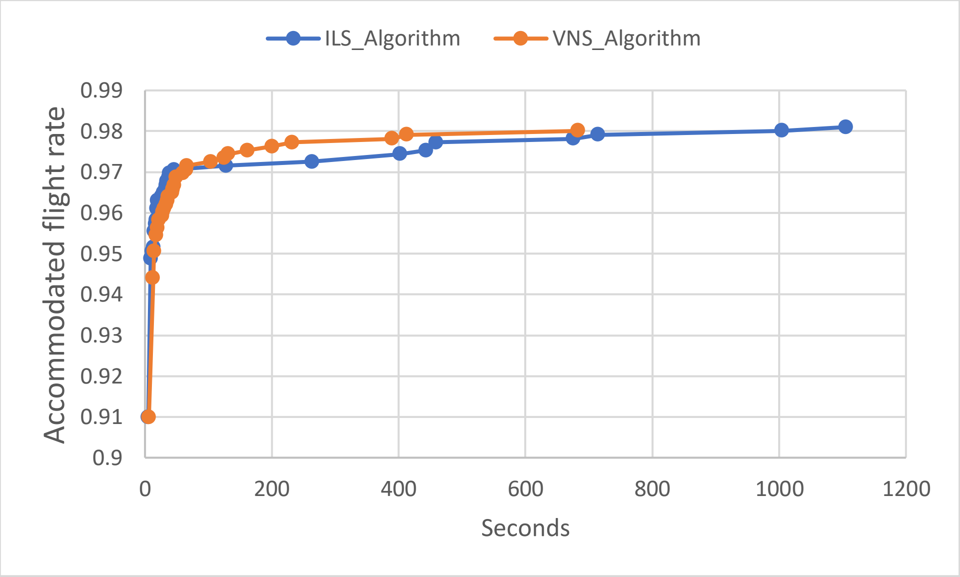

Figure 11: ILS and VNS Algorithms on medium size instances

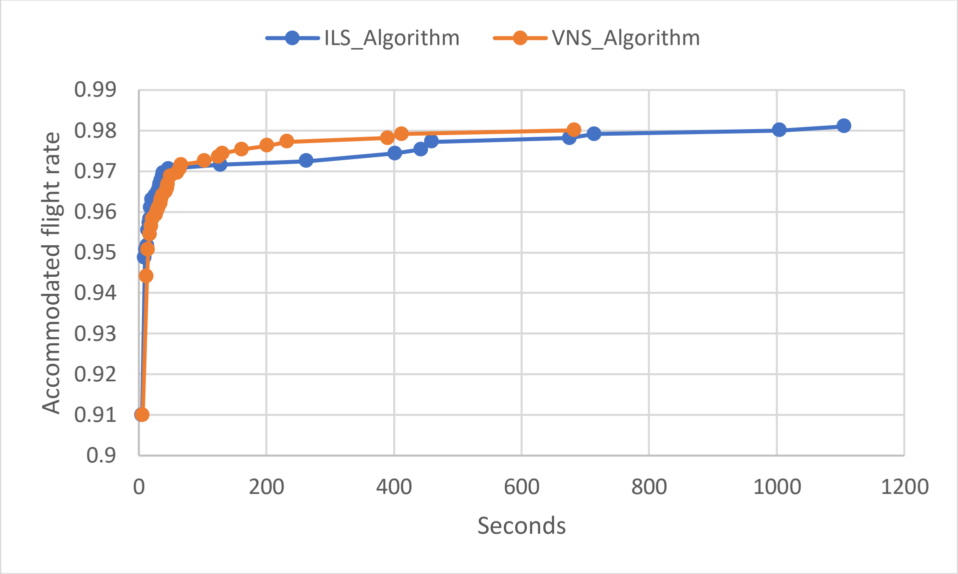

Figure 12: ILS and VNS Algorithms on large size instances

The experiments are performed in the following section by ignoring bold lines in pseudocode. To enable a better solution search, the timeout of algorithms was increased.

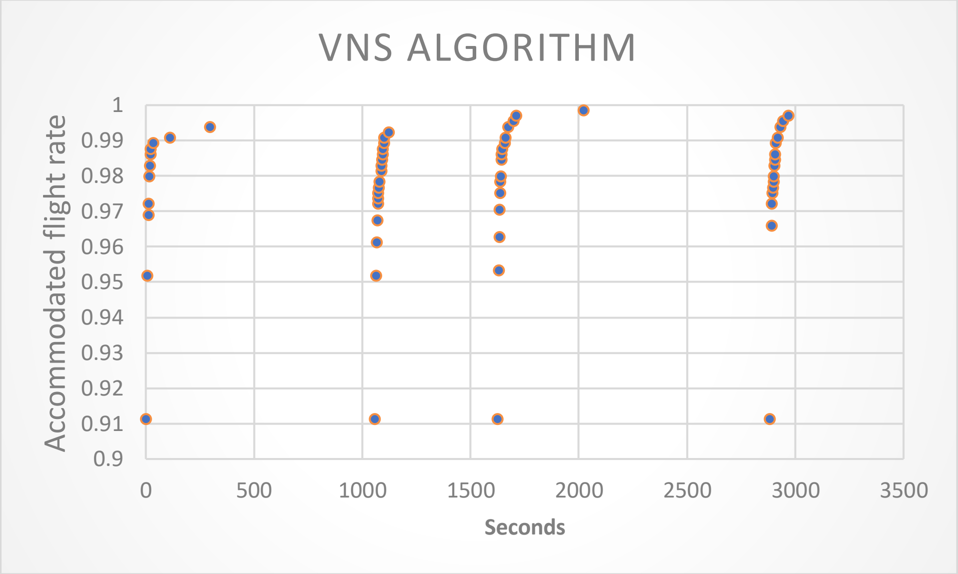

Figure 13: VNS Algorithm on a small size instance with timeout 18000

The ratio reached the 100% benchmark of accommodated flights after 14400 seconds. The algorithm started 20 times from the beginning and escaped the local optimum. Only four of them are shown in the chart.

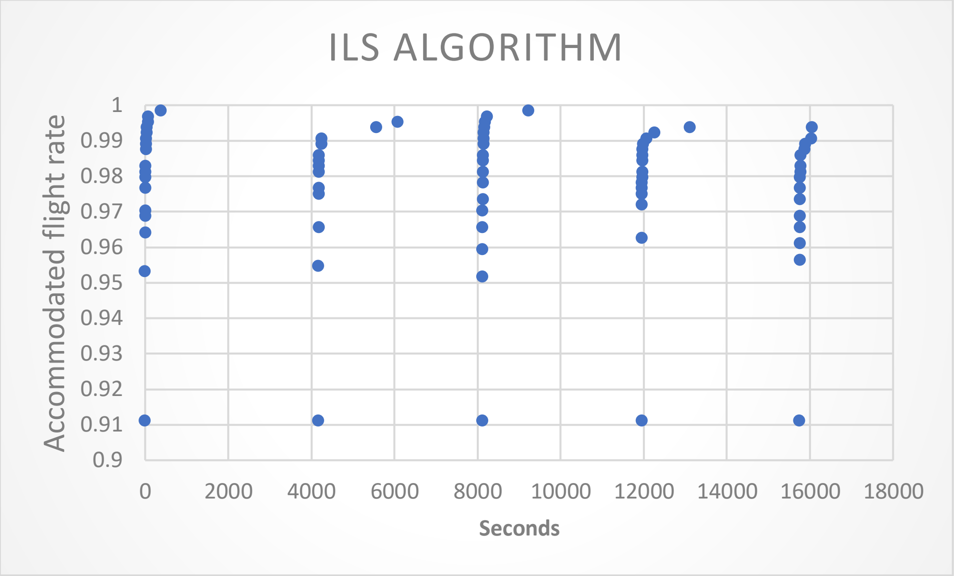

Figure 14: ILS Algorithm on a small size instance with timeout 18000

ILS Algorithm on small size instance could not accommodated 100% flight requests in 18000 seconds. The algorithm started 5 times from the beginning and could not escaped the local optimum. It reached a success rate of 99.8 percent in the middle of the timeout period but could not increase it within the remaining 9000 seconds.

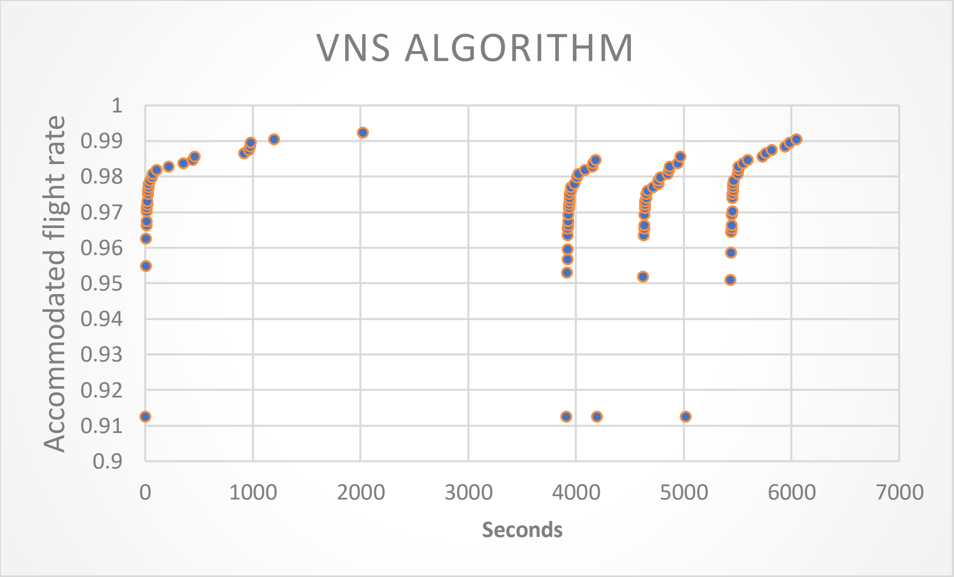

Figure 15: VNS Algorithm on a medium size instance with timeout 18000

The algorithm, which started 20 times from the beginning, could not receive a better accommodated flight rate than 99,2 %.

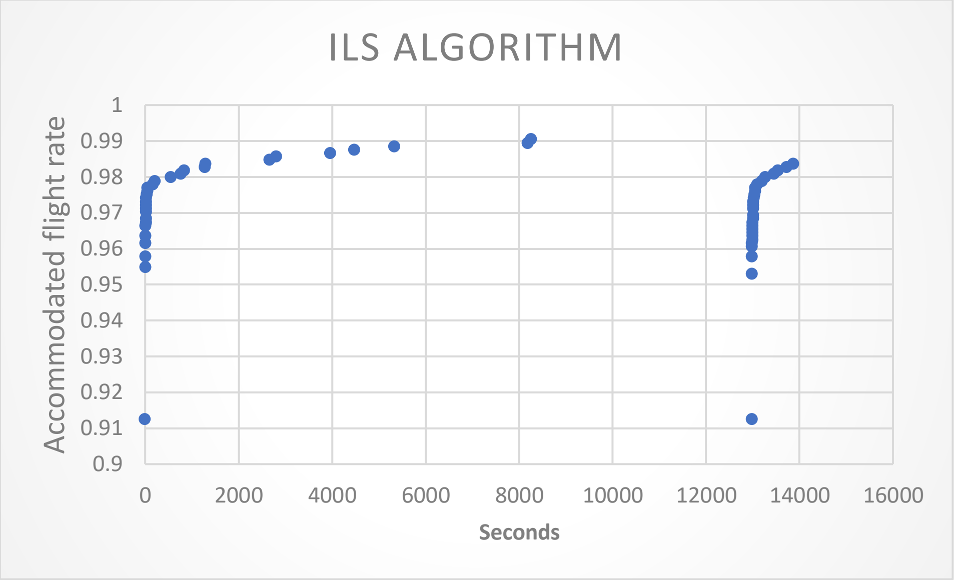

Figure 16: ILS Algorithm on a medium size instance with timeout 18000

The ILS Algorithm restarted the problem only once in 5 hours to escape the local optima, but the accommodated flight rate could not go beyond 99 %. In our medium-sized experiments, VNS provides better solutions within 5 hours. In the following, 8-hour experiments were carried out for the large-scale sample.

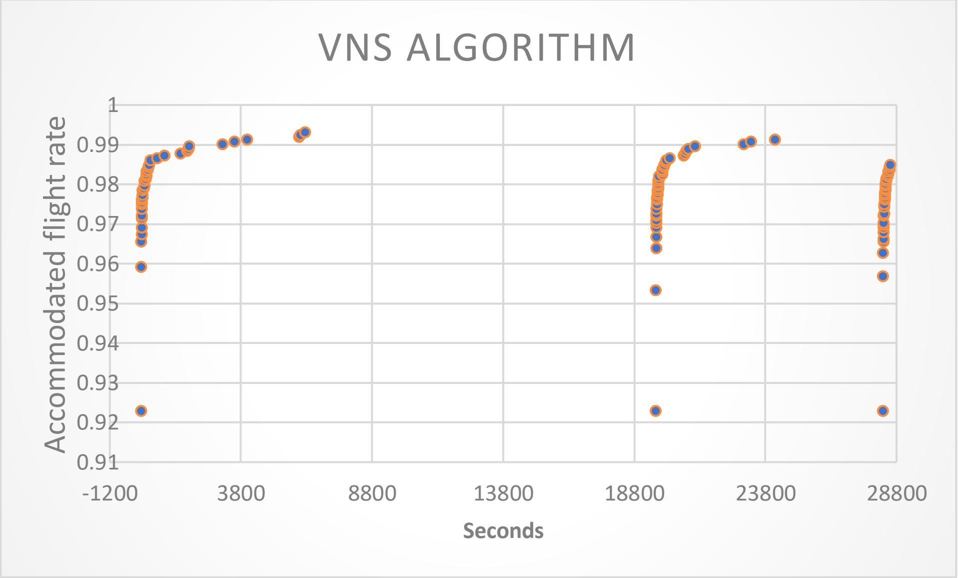

Figure 17: VNS Algorithm on a large size instance with timeout 28800

The VNS algorithm accommodated 99.3 % of the flight requests in slots within eight hours. The second trial of randomly generating solution functions exceed the time limit. The solution of the ILS algorithm as a result of experiment performed on the same flight data is shown below:

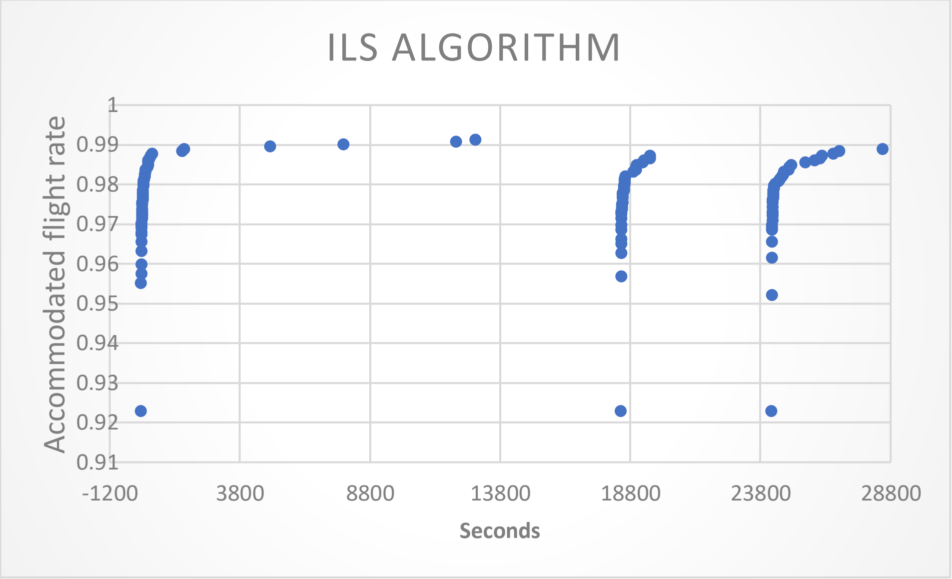

Figure 18: ILS Algorithm on a large size instance with timeout 28800

On the other hand, the ILS algorithm, using the same data, accommodated 99.1 % of the flight requests in slots within eight hours.

The results of the experiment revealed two different features of the VNS algorithm. First, the VNS algorithm provided better results in small samples than the ILS algorithm, albeit with a slight difference. Secondly, the VNS algorithm has achieved good results in a short time, but it has been very difficult to develop these results over time. Then, different large instances were run twice more with algorithms for 8 hours.

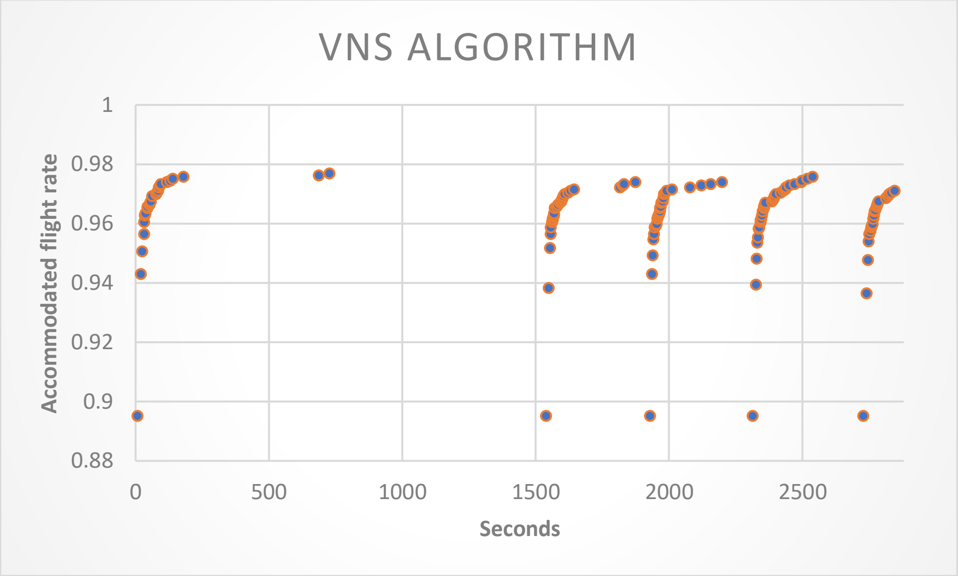

Figure 19: VNS Algorithm on a large size instance with timeout 28800

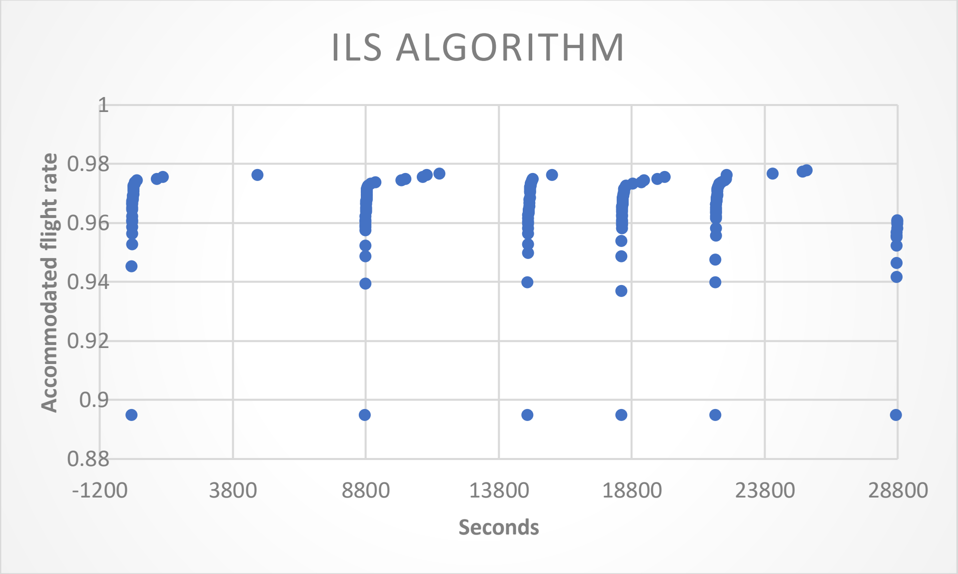

Figure 20: ILS Algorithm on a large size instance with timeout 28800

On the same instance, the ILS algorithm has reached 97.8 percent successful allocation rate in 8 hours while the VNS algorithm has reached 97.7 successful allocation rates in 8 hours. Figure 20 shows only a part of the solution seeking process of the VNS algorithm. The VNS algorithm has reached this result by starting over 38 times on this sample.

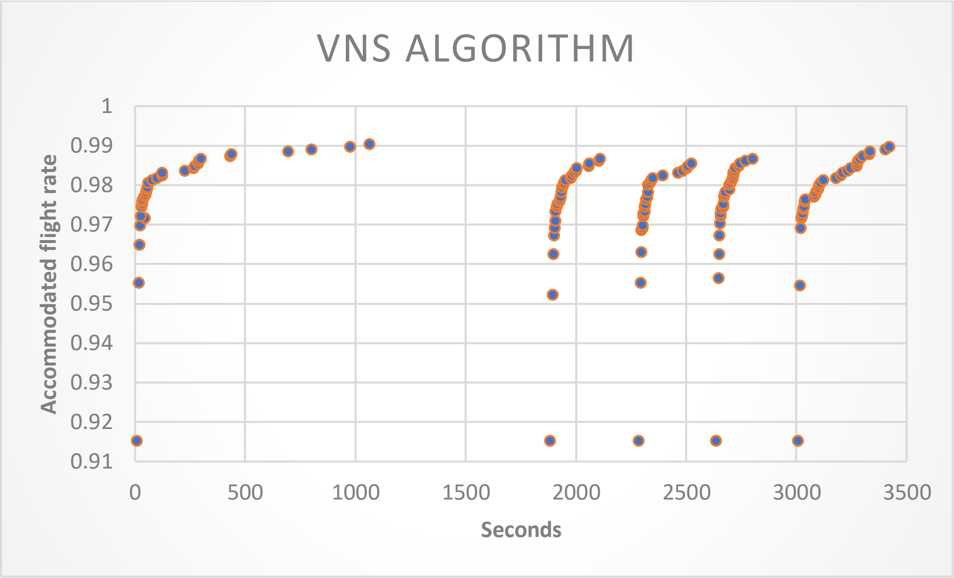

Figure 21: VNS Algorithm on a large size instance with timeout 28800

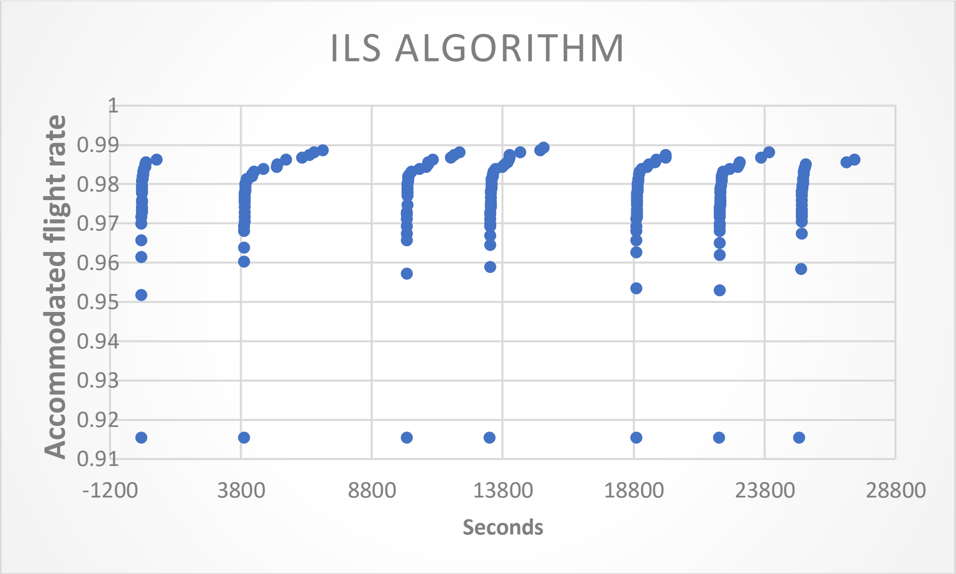

Figure 22: ILS Algorithm on a large size instance with timeout 28800

In the last experiment, the ILS and VNS algorithms have reached 98.9 and 99 percentage of successful allocation rate respectively. While the superiority of the VNS algorithm is noticeable in the small sample trials, the ILS algorithm provided close to the VNS algorithm and sometimes even better solutions as the sample grows. It is predicted that ILS algorithm would achieve successful solutions in larger scale experiments.

7. Delay Cost Coefficient

This section will cover the reasons and feasibility of the cost of the flight request which occurs when scheduling it forward or backward by a certain time interval. This cost coefficient is determined randomly between 20-30 in the experiment.

Delay costs for airline companies can be analyzed in three groups as soft, hard and internalized costs. Hard costs can be defined as costs occurring immediately after the delay (passenger compensation, etc.), while soft costs can be defined as costs with long-term consequences that do not immediately show up. Internalized costs are more personal losses that are theoretically not transferred to the airlines by passengers. Of course, it can be indirectly related to easy costs. Soft costs are closely related, for example, with consumer experience and future subjective decisions. The delays that may occur in the first allocation might be analyzed as hard costs (Cook & Tanner, 2015)

Most of the airplanes are rented by airline companies. Even if the planes are not rented, the airlines face heavy losses when the planes are not operating frequently. Delay cost varies depending on the model of the aircraft, its passenger capacity and the number of potential business class passengers on the flight. The time period of the day of the flight request plays a significant role as well. For instance, a flight delay at noon does not affect passenger demands much, whereas a flight delay in the morning or evening can reduce the demand profoundly. This cost factor might be specified by examining historical data. Another delay cost parameter can be the organizational service which takes place for each flight. Setting a working schedule of flight crew can cost more (Ball et al., 2010). Such factors should be taken into account when calculating a time interval delay cost of each flight request.

In the secondary slot allocation approaches, bid values of airline companies can be used instead of delay cost coefficient. Metaheuristic algorithms then search for the largest total bid value. In the other part of the thesis, some problems and alternative approaches in secondary allocation such as slot trading, auction, congestion pricing will be explained.

8. Trading Problem

Airline companies have to return the allocated slots until a certain time unless they plan to use them. Returns have to be made as soon as possible in order that the coordinators can re-allocate the slots better. The day of the return is approximately two months before the beginning of the season. Delayed slot returns are considered as unused when it comes to its slot status and reduce the airline's utilization rate in that slot. This may cause airline companies to lose their opportunity for the historical usage -Grandfather Rules-. Therefore, airline companies return the slots they do not plan to operate and contribute to the better slot allocation process (MacDonald, 2006).

Pursuant to the IATA Guidelines, exchange of slots between airline companies in Level 3 Airports is encouraged after the primary allocation. However, the secondary slot allocation rules and principles are not expounded in detail in the IATA Slot Guidelines. Since it differs regionally, problems occur due to the large number of participants and different authorities involved in the secondary slot allocation process which has a negative impact on the purpose of the whole allocation.

According to the Worldwide Slot Guidelines (2019), airport slots are not reserved certain aircrafts or flight numbers and can be replaced by flights or allocated aircrafts of other airlines. An important condition in this process is the approval of the airport coordinator to allow this change. This change should be updated in the slot monitoring. One-on-one replacement of slots by airline companies at third level airports is encouraged. Regarding the definition of a slot exchange, when an artificial exchange took place, the question arose whether one-side slot transfer was an illegal or legal slot intervention. Because of this slot mobility under the regulation mentioned by De Wit and Burghouwt (2008), Worldwide Slot Guidelines (2019) includes a current principle. If, in a situation involving the exchange of newly allocated slots, not allocated by grandfather rules, the coordinator may not approve the settlement when he or she is unsure that the exchange will improve the operations of both airlines. In this case, it is necessary to contact the airport coordinator and the airlines companies.

Slot swaps for compensation can only occur unless they are not prohibited by the laws of the country concerned. In addition, it is not allowed to transfer newly allocated slots until two equivalent seasons are operated, in order to prevent airlines from taking advantage of an improved priority such as new participation status. However, another principle "Slots may only be transferred to another airline that is serving or planning to serve the same airport.", which is stated by IATA in Worldwide Slot Guidelines (2019), is not very clear and may cause problems. The explanation how to prove that airlines plan to serve is not specified in the guidelines.

• 8.1 Secondary trading as a combinatorial exchange

Pellegrini, Castelli, & Pesenti (2012) proposed a market formalization of secondary trading of airport slots as a budget balanced combinatorial slot exchange.

The model

In addition to the input sets and parameters of the simultaneous slot allocation problem, the followings are required in the model:

A	Set of airline companies
F_a	Set of flights of the airline company $a \in A$
R_f	Set of feasible routes for flight $f \in F$
$I(j,t,r)$	1 if slot (j,t) ∈ (j,t)(K ∪ S) × T and belongs to $r \in R_f$ 0 otherwise
$S_{j,t}$	Capacity of sector j ∈ S at time interval $t \in T$
$G^a_{j,t}$	Number of slot (j,t), $j \in K$ and $t \in T$, *for* which airline $a \in A$ has grandfather rights
c^f_t	Function expressing the cost of deviating of t time intervals from the ideal slot
c^f_{dur}	Function expressing the cost of increasing duration of flight $f \in F$ one-time interval

Table 7: Additional input sets and parameters

The proposed market mechanism creates a route for the flight in the slot allocation process, allowing the sector capacities in the route to be taken into account.

Decision Variables:

$$w_{a,r} = \begin{cases} 1 \text{ if route r is allocated to } a, \\ \\ 0 \text{ otherwise.} \end{cases}$$

Furthermore, for each airline $a \in A$, p_a represents the total monetary amount paid or received in the system by a:
$p_a \in R$, payment made ($p_a < 0$) or received ($p_a > 0$) by a.

The objective function of this model contains only the sum of the overall shift costs imposed to the airlines:

$$z^* = min \sum_{a \in A} \sum_{f \in F_a} C_f ,$$

where here C_f represents the short notation for the cost paid for the single flight f, that is:

$$C_f = \sum_{r \in R_f} w_{a,r} \left\{ \sum_{t \in T} I(dest_f, t, r) c^f_{|t-at_f|} \right. \\ \left. + c^f_{dur} \left[\sum_{t \in T} t \Big(I(dest_f, t, r) - I(orig_f, t, r) \Big) - (at_f - dt_f) \right] \right\}.$$

Let $I(dest_f,t,r)$ be an indicator which equals to one if a slot at airport or sector j at the time interval t belongs to route r, and zero otherwise. As a result, the first part of the cost penalizes a different arrival time interval than the intended one. The shift costs are calculated on arrival time (at_f) basis because during secondary trade airlines may already be carrying out some organizational tasks and even selling tickets. Thus, the mechanism minimizes the increment of the cost due to the subsequent allocation phase. In addition, if the subsequent allocation phase reduces flight f duration, airline companies have opportunity to have shorter routes.

The second part of the cost penalizes the longer flight duration than the planned one. $\sum_{t \in T} t \Big(I(dest_f, t, r) - I(orig_f, t, r) \Big)$ clarifies the flight f duration along route r. $\sum_{t \in T} t \Big(I(dest_f, t, r) \Big)$ is equal to arrival time of flight f at the destination $dest_f$ because all the total values that differ from the arrival time are equal to zero. Likewise, $\sum_{t \in T} t \Big(I(orig_f, t, r) \Big)$ is equal to departure time of flight f at the origin $orig_f$. Indirectly, the combination of the two terms in the cost calculation penalizes a departure time interval different from the desired. The cost C_f equals to zero if the flight is assigned to the ideal arrival slot in the scheduled time.

Pellegrini, Castelli, & Pesenti (2012) assume that the cost function c_{dur}^{f} is constant for all $f \in F$ and $c_t^f = \alpha_f t^{\beta_f}$ has structure, where α_f and β_f are nonnegative parameters with $\alpha_f < c_{dur}^{f}$ and $\beta_f > 1$. The condition $\alpha_f < c_{dur}^{f}$ ensure that changing the departure and landing times is preferred rather than prolonging the flight duration.

Constraints

The constraints of the model are as follows:

- the capacities of airports and sectors are taken into consideration,

$$\sum_{a \in A} \sum_{f \in F_a} \sum_{r \in R_f} I(j,t,r) w_{a,r} \leq S_{j,t} \qquad \forall j \in S, t \in T;$$

$$\sum_{a \in A} \sum_{f \in F_a : orig_f = j \vee dest_f = j} \sum_{r \in R_f} I(j,t,r) w_{a,r} \leq K_{j,t} \qquad \forall j \in K, t \in T;$$

- the grandfather rights are applied for each airline companies a,

$$\sum_{f \in F/F_a : dest_f = k \vee orig_f = k} \sum_{r \in R_f} I(j,t,r) w_{a,r} \leq K_{j,t} - G_{j,t}^{a} \qquad \forall j \in K, t \in T, a \in A;$$

- a complete route is allocated for each flight. By this means, airline companies also have their own routes,

$$\sum_{r \in R_f} w_{a,r} = 1 \qquad \forall a \in A, f \in F;$$

- the budget balance is provided,

$$\sum_{a \in A} p_a = 0\,;$$

- the individual rationality is ensured,

$$\sum_{f \in F_a} C_f - p_a \leq \sum_{f \in F_a} \left\{ c^f_{max\left\{at_f - \underline{T}^f_{orig_f}, \overline{T}^f_{orig_f} - at_f\right\}} + c^f_{dur}\left[\overline{T}^f_{dest_f} - \underline{T}^f_{orig_f} - \left(at_f - dt_f\right)\right] \right\} \qquad \forall a \in A.$$

The left side of the constraint is the total cost of an airline minus the amount of monetary payments received in this mechanism. The right side of the constraint is the representation of the maximum acceptable cost which is maximum acceptable shift cost plus cost of maximum acceptable flight duration change. An airline company is volunteer to accept additional costs only with new flight requests.

Pellegrini, Castelli, & Pesenti (2012) conclude that the proposed combinatorial exchange offers to airlines a significant cost reduction in secondary allocation. However, the main purpose of the slot allocation should be initially determined. According to IATA (2019) Guidelines the privileged purpose of the slot allocation, which is part of the airport coordination, is to ensure the most efficient use of the airport's infrastructure. Even if the main objective in this model does not comply with the IATA (2019) Guidelines, it would be beneficial to the airline companies in terms of providing a fair service. Furthermore, this mechanism takes into consideration the sector capacities in the route during the slot allocation process.

• 8.2 Experiences of secondary trading

In regions where the slot trade is officially accepted, airline companies will try to get as many slots as possible in the primary allocation, as they can own the slots at the congested airport for free. Slots that are not planned to be used return to the slot pool after a certain period of time without creating a financial disadvantage to their previous owners. These slots are then made available to competitors and / or new participants. But this inefficient allocation harms the overall competitiveness of the market. Slot trading occurs in a properly created marketplace available to the public by pricing by the slot purchaser. Secondary slot trading is done regardless of the initial allocation of the slots and aims to increase efficiency. Airlines will volunteer to sell slots that are not used and/or cannot earn enough income.

	Acquirer	**Vendor**	**Number of daily slot pairs**	**Sum paid GBP million**	**Value per slot pair GBP million**
1998	BA	Air UK	4	15.6	3.9
2002	BA	BA Connect	5	13	2.6
	BA	SN Brussels	7	27.5	3.9
2003	BA	SWISS	8	22.5	2.8
	BA	United	2	12	6.0
2004	Virgin	Flybe	4	20	5.0
	Virgin	Air Jamaica	1	5.1	5.1
2006	BA	BWIA	1	5	5.0
2007	BA	Malev	2	7	3.5
	BA	BMI	7.3	30	4.1
2008	Continental	GB Airways/ Alitalia/ Air France	4	104.5	26.1
2013	Delta	Not Known	2	30.8	15.4
	Etihad	Jet	3	46.2	15.4
	Not known	Alitalia	3	67	22.3
	Qantas	Flybe	2	20	10.0

Table 8: Slot Trading Experiences in Heathrow

(Ranieri, Alsina, Castelli, Bolic, & Herranz, 2014)

Since the data about the value of slots owned by some airlines are sensitive to trade and therefore kept confidential, there is no bargaining mechanism that helps making transactions efficient. There is a risk that airline companies which have dominant position at airports can use their superior financial power by preventing the slots from entering the market in advance. In other words, it causes loss of competition in the slot trading system. However, at some third level airports in the USA, it has been observed that the dominant airline companies are in search of efficiency in slot use rather than anti-competitive practices. Experience in the US and the UK regarding secondary markets shows positive results. The data claims that this system can encourage competition to some extent and provides convenience to new entrants to the market (Kociubiński, 2013).

Slot trading is permitted in the US for air carriers in 1985 by the update of ‘Buy-Sell Rule’. “US Airways” and “Delta” companies that are known for carrying out various slot trading operations in America. Secondary slot trading in many cases is seen as a tool that helps to increase the utilization of airport capacity by increasing slot mobility. There are many slot exchanges for timing adjustments, but few of these adjustments are permanent or long-term transfers. Most of the operations in the secondary trade happen in the form of leasing, unlike open sales.

There is no official market for slot trading in Europe. However, in some airports, a gray market has been created for trading and leasing transactions that are realized through fake and artificial exchanges. The airport, where secondary trade first took place in Europe, is Heathrow airport in London, one of the most crowded airports in Europe. Airport coordinators determined some fake exchanges at other airports like Frankfurt, Vienna and Düsseldorf although the secondary slot trade was not transparent. Some examples of slot trades reported in Heathrow during the period 1998-2013 are shown in the Table 5. The information in this table has been acquired from the Airport Coordination Limited (ACL) reports.

8.2.1 Airport Coordination Limited (ACL)

ACL is the world's leading Airport Slot coordinator company, which operates simultaneously with 46 airports around the world to help airport coordinators, airlines and passengers to use the limited capacity of airport infrastructure more efficiently. ACL, which was formed in 1991, coordinates 3.8 million flights each year. The ACL team includes experts who support and develop the entire air transportation system, offering worldwide slot trading, data sales, analysis and consulting services. The number of airports that ACL has coordinated since its establishment is shown in the Figure 23. It coordinates domain services dynamically and responds to 99% of its requests within one day and 90% of them right away. ACL created a website that illustrates the details of the slot transactions: www.slottrade.aero (Ranieri, Alsina, Castelli, Bolic, & Herranz, 2014).

The Online Coordination System (OCS) has been developed for ACL by Prolog Development Center (PDC). OCS is a system that allows all airports to access the database of the airport coordinator and receive information very quickly. Thanks to OCS, airports may provide usable real-time slot information and authorized users can make online offers for multiple airports simultaneously because OCS contains many Slot Coordination Authorities such as Airport Coordination Denmark, Changi Airport Group, Airport Coordination Sweden, etc.

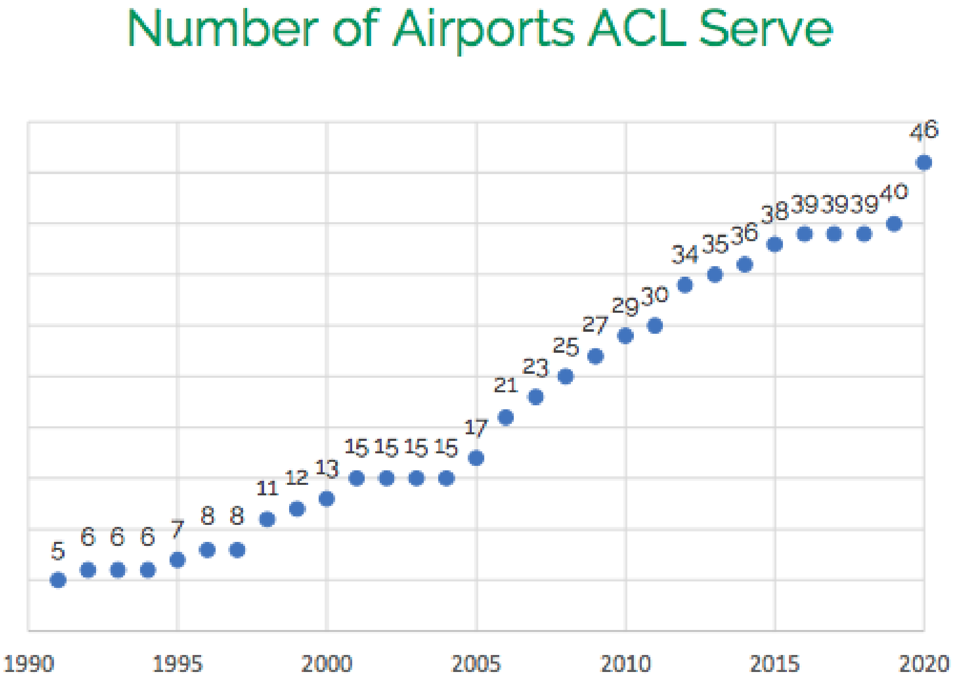

Figure 23: Number of Airports ACL Serve

• 8.3 Auction

The auction mechanism may be an alternative approach to the slot trading problems. Airlines have the opportunity to sell their belongings to the best bidder thanks to the auction mechanism. In the literature, many authors have mentioned auctions as a useful method to reveal the actual values of slots at airports and increase slot utilization. Gruyer and Lenoir (2003), Brueckner (2009), and Jones et al. (2004) can be cited. The Federal Aviation Administration offered auctions for a number of slots in New York in 2008, but this method was later revoked. In economic theory, when the auction is well designed, the willingness of the purchaser to pay shows the well-being of this commodity, which reflects the social (Nicolas Gruyer, 2003) (Brueckner, 2009) (Jones et al., 2004) welfare in case of a competitive market.

Lenior (2016) argues that it may be useful to auction some of the slot series every year to improve the current EU slot allocation, to adapt to the changing market conditions and give new airlines the chance to enter third level airports. As mentioned by Lenior (2016) this proposal may pose difficulties such as design problem, high cost of auctions and the industry's potential reluctance. It is also predicted that dominant carriers may get monopolizing slots. It can be argued that this system may be at risk of crushing new entrants by dominant carriers, because dominant carriers would bid much higher prices than new entrants and therefore would not allow new firms to enter the market. Offering just a certain percentage of slots to auction each year could reduce that risk.

The main goal in slot auction is allocation efficiency, but it is also necessary to consider the characteristics of airline operations related to airline companies' schedule planning. From the perspective of airline companies, a particular slot combination has a higher value than the sum of the individual value of each slot in this combination. It seems impossible to consider the schedule planning integrity of airline companies in a single slot auction system. Therefore, a single-slot-one-auction system for separate areas cannot provide allocation efficiency. One of the possible solutions to fix this problem is the Vickrey auction (Vickrey-Clarke-Groves System). Each bidder firm provides a complete valuation list, one for each possible item package (Ausubel, 1999). In the next step, the auction determines the most efficient allocation based on the values presented. The bidders are then asked to pay the opportunity cost to participate in the auction In other words, the company that purchases the slot pays the opportunity costs of other participants in the auction (Kociubiński, 2014).

Another auction mechanism is the clock-proxy-auction (Cryptographic Combinatorial Clock-Proxy). A clock auction and a proxy auction are two main phases of this mechanism. The first stage provides simple and transparent price discovery, while the second stage improves efficiency. In the clock stage, the auctioneer announces the slot prices and the bidders call for the number of slots they want. Slot prices are increased when demand exceeds the supply, and a new round starts. This phase ends when there is not much demand for any time period. The main purpose of this phase is to facilitate price discovery in order to eliminate the risk of the bidders paying an excessive price for an unnecessary area. At the end of this stage, airlines will be able to estimate the commercial value of each slot (Kociubiński, 2014). Airline companies then determine the values of the areas they are interested in and then report these values to a proxy agent. Using the values reported in the X round, proxy determines the potential profit for a possible bid. It then offers the buyer a bid corresponding to the maximum potential profit. This stage is designed to promote efficiency.

Another option for auction is the first-price package auction (combinatorial auction) which operates on all or nothing basis. The basic principle of this method is that the airline offers a certain number of slot packages, but only pays when it receives the slot package as a whole. As mentioned earlier, the value of a given slot combination for participants is greater than the combined value of an equal number of separated slots. In this system, it is quite complicated to determine the bidder's winner and to use the full capacity efficiently (Kociubiński, 2014).

• 8.4 Congestion Pricing

Congestion pricing focuses on driving the market economy to regulate demand-driven traffic. Costing pricing support to improve the flow of traffic at airports by flattening the demand during busiest hours and increasing the demand during calmer times (Ranieri, Alsina, Bolic, Castelli, & Herranz, 2014).

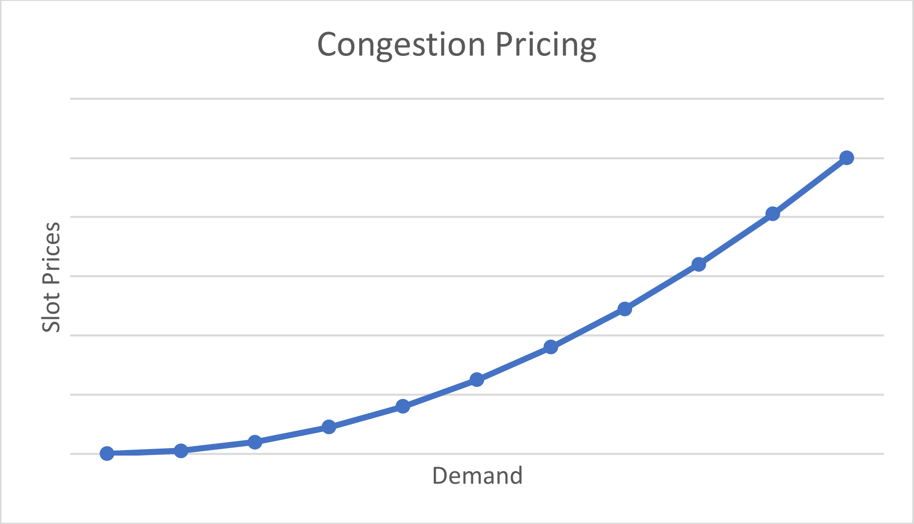

Figure 24: Congestion Pricing

Consumers (Passengers) consider peak hour flights as a high-quality product, and non-peak time flights as a low-quality product. This logic of the consumers in this system reflects the commercial value of the slots associated with the prices of airport services and contributes to the efficiency of the system. The biggest drawback in this system is the competitive balance of slot prices, which is only released after slots are allocated to all airlines. In the real-world scenario, prominent slot combinations have greater value for airlines. At the end of this system, a market cleaning needs to be reimplemented and the airline companies are urged to perform certain clearing transactions. However, it is not predictable if airport coordinators or regulators can calculate clearing prices in the market. While the total number of available slots at the airport is known, the value of these slots for airlines is unknown. This uncertainty can lead to two different consequences. In the first possible scenario, if the price threshold is set to an insufficiently low level, it cannot provide the expected outcome of the demand for leveling between the peak and off-peak. In the second scenario, if the congestion fee is set to an excessive level, airline companies may abandon the inclusion in the system (Ranieri, Alsina, Bolic, Castelli, & Herranz, 2014).

• 8.5 Incentive-Based

By introducing preventive incentives to avert primary delays and foresee the spread of secondary delays, Grunewald (2016) argues that prioritizing the usage of resources at congested airports improves resource utilization. Thus, process stability ad punctuality at airport infrastructure can be realizable. If the operation in slots is analyzed as a queuing theory, the simple model can be expressed by the FIFO (first-in-first-out) method. The service is provided in order of its arrival at the station. However, the queuing strategy can allow pending in the queue to influence ranking by giving specific non-preemptive priorities (PRIO-NP). Departure and landing at the airports are operations with different priorities. PRIO-NP is often used when allocating slots at airports because, while space is limited for aircrafts in the final approach, departure traffic can wait until the runway is available.

It is mentioned that the diversification of the product (slot) available for use in this alternative allocation method will increase the efficiency of the process. The diversification of the slots at the airport might enable to reduce the processing time of the slots and to provide better service according to the customers' demands. Classifications, which are made according to these priorities, and slot diversity are used only when the demand cannot meet the capacity.

Another component of the incentive-based allocation system are performance-centered priorities. Planned flights are prioritized before the flight takes place. If the flights arrive at the airport in the scheduled timeframe, they are allocated to the slots according to these priorities.

But if they arrive at the airport before or after the scheduled timeframe, they lose their priority. Incentive-based slot allocation is an approach that will help airports to use their capacities efficiently when they encounter an unexpected situation and the demand-capacity balance is break down.

9. Conclusion and Recommendations

This thesis focused on two stages of slot allocation. Firstly, the problem of simultaneous slot allocation is simulated with two metaheuristics, taking into account the capacity of Level 3 airports. Then, trading problems and different alternatives in secondary allocation are mentioned.

The current procedure begins with the formation of the slot pool after the grandfather rules are applied by the airport coordinators. As shown in the graphics and tables, flight requests are accommodated in the slots at the airports in a short time thanks to the algorithms. Then the algorithms continue to search locally for cheaper solutions. It is precisely foreseen that the usage of metaheuristic algorithms in the primary allocation will be beneficial and fair. Although the two algorithms provide similar solutions, the VNS algorithm has been found to reach better solutions in time than the ILS algorithm. However, the ILS algorithm continued to find better solutions over a long period of time. As a future study, more realistic larger samples can be tested with algorithms on more powerful computers.

Subsequently, the airport coordinators continue their secondary slot allocation process in bilateral meetings with airlines. The main purpose of the whole slot allocation is the efficient allocation of a restricted airport capacity. It needs be admitted that the flexibility of the slot allocation system is actually a tool rather than a purpose (Authority, 2001). Secondary allocation or trade help to achieve its goal of operating in the most efficient way. In order to manage the overall process more transparently and fairly, it is recommended that airport coordinators inform airline companies continuously and utilize the algorithms in secondary slot allocation as well. Otherwise, it is likely that although the airport coordinator allocates slots to airline companies as part of the usual airport service, it may cause unfair trade between airlines.

Based on the experience of the secondary allocation in the EU, the system does not work efficiently because new entrants to the market send an insufficient number of slots back to the slot pool. Uncertainty in the secondary allocation can be a negative result as the airport congestion and related service disruptions continue to grow. Because it causes ever-increasing losses in airlines and the entire European economy. Each proposed and discussed method has its advantages and disadvantages for the various groups involved in the decision-making process. Therefore, obtaining political support is inevitable in order to implement these methods. For this reason, one possible but very difficult solution is the cooperation of the institutions that will reach consensus and have political support (Kociubiński, 2014). For example, the ACL company that was established in 1990 and whose number of coordinated airports reached 46 in 2020. That proves that an institution working coordination with the airports in different countries and receiving the support of the countries' authorities, manages the process more efficiently.

In addition to the complexity of the problem, another factor that needs to be considered is the issue of competition policy. There are a few significant points that matter according to the analysis of proposed methods in-depth. Probably the most important of these is that the dominant airline companies in the market are prevented from using market power (Kociubiński, 2014). The dominant attitudes of the companies against the competition, as well as the mergers and acquisitions, should be prevented. Since slot allocation trading is a monetary transaction, there should not be any problem of its compliance with state rules. However, it would be quite difficult for local authorities to decide which alternative management will be the best solution for that region.

As mentioned earlier, compared to Europe the number of Level 3 airports in America is very low. The slot allocation system in America (except Level 3 airports) is based on 'the-first-come-first-served' principle which provides airline companies with the very efficient usage of capacity and easier access to airports. However, this system causes delays. While delays occur less often in the EU system, economists argue that this system has negative effects on the economic efficiency (Lenoir, 2016). The system in Europe can adversely affect the size of the aircraft, thereby affecting the air transport system. It is thought that it may cause "slot hoarding" and "babysitting", which involves the use of small aircrafts and / or low load factors in order to keep historical slots. This phenomenon has been observed in the experiment conducted in America (Lenoir, 2016). Lenoir (2016) also mentioned that the negative effect of grandfather rules on the aircraft's size was reduced by the increase in air traffic. Looking at the historical data, it seems that no particular efforts need to be put forth to increase air transportation. Furthermore, certain limitations may be imposed on the plane's size depending on the flight's purpose.

Although increasing airport capacity might be very efficient, it is not always applicable. It could be beneficial to implement secondary trade with a combination of various alternatives.

In other words, it is anticipated that allocating a certain portion of the slot capacity for each of the above-mentioned approaches can increase slot utilization and competition. In this way, it may be possible to minimize the negative consequences of alternative approaches. Experiences and historical data are very valuable in entire slot allocation due to the complexity of the process. It is apparent that the coordination of airports and local regional authorities brings high efficiency.

My personal opinion is to increase the number of organizations, which coordinate more airports simultaneously such as ACL, and to develop better alternative solutions by making use of experiences of the employees in these organizations and the results of the methods applied so far. In addition, metaheuristic algorithms such as Iterated Local Search (ILS) and Variable Neighborhood Search (VNS) can assist competent authorities in slot allocation task under various complex constraints, like many of the real-world optimization problems.

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