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Scheduling Aircraft Landings to Closely Spaced Parallel Runways

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Abstract— **An optimization model for a scheduling problem for closely spaced parallel approaches has been formulated. It takes temporal, pairing, sequencing, separation route and grouping constraints into account. Simulations investigated possible advantages of advanced scheduling methods over first-come-first-served scheduling. Also, this study evaluated the performance differences between the computation of optimal solutions using mixed integer linear programming and computing solutions using genetic algorithms. The influence of the scheduling method, as well as the influence of varying the sizes of the pairing and estimated arrival time windows, have been investigated. A set of 20 aircraft, distributed over 30 minutes, was used as traffic data. Inputs to the model were the earliest and latest estimated arrival times, aircraft wake category, aircraft pairing group and route information. A schedule at a specific coupling point where aircraft are coupled for parallel approach was then computed. It is generally expected that closely spaced parallel approaches greatly enhance arrival throughput. The results of this study underpin this assumption. Further findings were: (1) for a sufficiently varied traffic mix, advanced scheduling methods can improve arrival throughput by approximately one parallel approach pair per half an hour compared to first-come-first-serve scheduling in visual meteorological conditions. Average delay can be reduced over first-come-first-serve scheduling in visual meteorological conditions by up to 36%. (2) schedules computed by an improved genetic algorithm are of similar quality as optimal solutions and can be made available after short computation times; (3) when minimizing makespan i.e., the arrival time of the last aircraft in a sequence, the size of the estimated arrival time window does not influence the characteristics of the computed schedules.**

Keywords-closely spaced parallel approaches; sequencing; scheduling; genetic algorithms

I. INTRODUCTION

Air traffic control (ATC) is required to provide safe and orderly operations, executed in an expeditious manner [1]. For this purpose, ATC needs to utilize fully the existing infrastructure, as well as employ new procedures and technology, to prepare for forecasted traffic demands. Establishing safe and efficient schedules for simultaneous aircraft landings to closely spaced parallel runways is one way to enable an increase in capacity at hub airports without increasing airport footprint. Furthermore, capacity may be stabilized if these operations are possible across a wide range of weather conditions [2].

Previous research has examined arrival scheduling. In 1976, Dear studied possible improvements on arrival sequence using the concept of constrained position shifts (CPS) in the arrival sequence [3]. Psaraftis presented a dynamic programming approach to optimize arrival aircraft order and used the advantages of CPS to reduce computational difficulty [4]. Heuristics, for example genetic algorithms, have been applied for arrival scheduling [5], [6], and [7]. Several publications address the two or multiple runway scheduling problem, or point out that the single runway problem could be extended. Examples are [8], where the aircraft landing problem was modeled as a special version of machine scheduling problem and [9] where aircraft landings were investigated under CPS using dynamic programming. Also in [10], analytical models were used to compute the ultimate arrival capacity using the staggered approach and the steeper approach procedure. However, no work has been published yet that describes the computation of arrival schedules for parallel approaches to dependent, very closely spaced runways.

The study described in this paper addressed some of the shortcomings of the prior work. A scheduling and sequencing model was developed describing the constraints of an advanced, future concept for very closely spaced parallel approaches (VCSPA) operations. The objective function tries to minimize the arrival time of the last aircraft in a sequence (makespan) given the earliest and latest arrival times of the aircraft in a set.

The goal of this paper is to compare first-come-first-served (FCFS) scheduling methods and advanced scheduling methods (mixed integer linear programming, genetic algorithms) based on a number of parameters. Results from 45 scenarios are presented. Arrival schedules are assessed that were computed using five different scheduling techniques, varying sizes of the pairing time window (PTW) and estimated arrival time window. The results are presented in terms of their makespan, average delay and required computation times.

II. BACKGROUND

The scenario computations carried out in this study are based on the Terminal Area Capacity Enhancing Concept

(TACEC) developed by Raytheon [11]. TACEC considers an aircraft pairing when aircraft are approximately 30 minutes from the terminal boundary. The actual coupling for approach between two aircraft is intended to occur 12 NM from the runway threshold. After that coupling the aircraft converge over a distance of 10 NM. For the last two nautical miles to the threshold the aircraft are on parallel flight path segments. The trailing aircraft is required to stay in a strategic safe zone (Fig. 1). It is defined by the safe and unsafe along-trail separation distances for following aircraft.

When the trailing aircraft is flying in the safe zone, it is situated a certain minimum time behind the lead, and thus, minimizes the risk of collision in case of a blunder of the lead. This time is referred to as the Lower Pairing Bound (LPB). The trailing aircraft needs to be ahead of a defined rear boundary, referred to as the Upper Pairing Bound (UPB), in order to avoid wake vortex encounter. Aircraft are intended to be scheduled to a coupling point (Fig. 2).

It is envisioned that an aircraft trajectory predictor computes estimated times of arrival of the aircraft at the coupling point assuming an unimpeded flight. Throughout this study, these times are referred to as nominal estimated time of arrivals (ETAs). Furthermore, it is assumed that for all approaching aircraft within a scheduling horizon all possible ETAs to the coupling point are being computed, taking into account for example, vectoring or speed adjustments. With these times a window between the earliest possible ETA (E-ETA) and latest possible ETA (L-ETA) is obtained. For simplicity, a continuous time window is assumed. Finally, it is envisioned that once a new arrival schedule is computed, the new scheduled times of arrival (STA) are handed back to the trajectory synthesizer which in turn computes for each aircraft the respective trajectory to the coupling point.

Problem statement: Given the earliest and latest possible arrival time of all aircraft in a set, the objective is to schedule the aircraft to a VCSPA coupling point such that the arrival time of the last aircraft in a set (makespan) is minimized, subject to temporal, pairing, sequencing, separation, route and VCSPA-grouping constraints.

For the formulation of the optimization program the decision variables z_{ij} and y_{ij} are used. z_{ij} equals one if aircraft i and j are paired for parallel approach and i is leading j, and zero otherwise. y_{ij} is set to one if two aircraft are not paired for parallel approach and aircraft i is leading j. The variable t_i describes the scheduled time of arrival of an aircraft i at the coupling point. The model can be mathematically defined by the following Mixed Integer Linear Program (MILP), minimizing the scalar variable s using $O(N^2)$ variables and $O(N^3)$ constraints:

Objective: **min: s**

s.t.: $$s \geq t_i \quad \forall i \in (1,...,N). \tag{1}$$

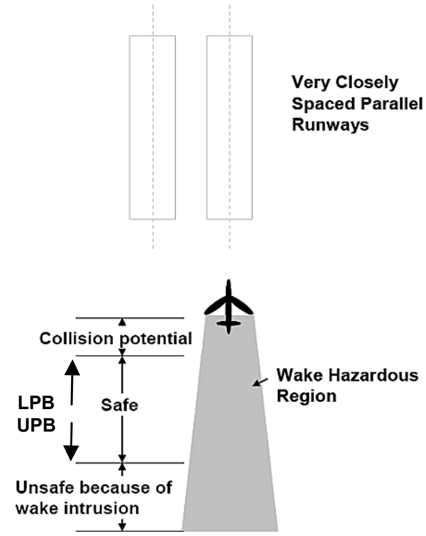


Figure 1. "Safe Zone" concept for Closeley Spaced Parallel Approaches.

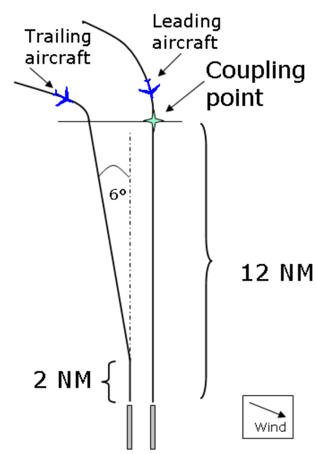


Figure 2. Terminal Area Enhancement Concept: coupling point and final approach segments.

Temporal constraints: The scheduled time of arrival t_i of aircraft i, may not be earlier than the E-ETA, $t_{i,E\text{-}ETA}$, and no later than its L-ETA, $t_{i,L\text{-}ETA}$.

$$t_i \in [t_{i,E-ETA}, t_{i,L-ETA}], \ \forall i \in (1,...,N) \tag{2}$$

Pairing constraints: For VCSPA to two runways, at most two aircraft may be in a pair. This can be formulated as follows:

$$\sum_j^N z_{ij} \leq 1 \quad z_{ij} \in \{0,1\}, \forall i \in (1,...,N), \tag{3}$$

$$\sum_{i}^{N} z_{ij} \leq 1 \;\; z_{ij} \in \{0,1\}, \forall j \in (1,\ldots,N). \tag{4}$$

Sequencing constraints: For all

$$i, j \in (1,\ldots,N),\ i \neq j:$$

$$z_{ij} + z_{ji} + y_{ij} + y_{ji} = 1,\ z_{ij}, z_{ji}, y_{ij}, y_{ji} \in \{0,1\}. \tag{5}$$

Equation (5) states that either aircraft i is paired with aircraft j or vice versa, or that aircraft i and j are not paired and i is leading j or vice versa.

Separation constraints: Sufficient separation needs to be provided between the aircraft in a pair as well as between pairs and single aircraft. Modeling a two runway problem the triangle inequality i.e. $sep_{ij} + sep_{jk} \geq sep_{ik}$ is not valid for all aircraft sequences. Paired aircraft need to provide less than the required minimum separation. Fig. 3 shows an example where the binding separation constraint is between aircraft i (Large) and k (Heavy). On the left side of the figure aircraft k provides the correct separation to its direct leader but violates the separation to aircraft i (Heavy). The triangle inequality i.e. $sep_{ij} + sep_{jk} \geq sep_{ik}$ does not hold. Correct separation needs to be provided between both aircraft in a pair and the aircraft trailing the pair.

The constraint (6.1) enforces the correct separation between single and paired aircraft, between two single consecutive aircraft, and between pairs of aircraft. M is a sufficiently large constant and sep_{ij} is describing the required separation between aircraft i and j. Four cases may occur:

a) aircraft i and j are paired, aircraft k and l are not,

b) aircraft i and j are paired, and aircraft k and l are paired,

c) aircraft i and j and k are not paired

d) aircraft i and j are not paired, but aircraft j and k are.

For all

$$i, j \in (1,\ldots,N),\ i \neq j:$$

$$t_j - t_i \geq -(y_{ji} + z_{ji}) \cdot M + y_{ij} \cdot sep_{ij}, \quad y_{ji}, z_{ji}, y_{ij} \in \{0,1\} \tag{6.1}$$

For both cases, when a single aircraft or a pair of aircraft is following a leading pair, the model enforces separation between both of the aircraft in the leading pair to the next two aircraft in the sequence. This is shown in the left half of Fig. 4. The binding separation constraint in this example is between aircraft j (Heavy) and l (Large). When two pairs are following each other the correct separation needs to be tested between all aircraft of both pairs. However, if two single aircraft, in this case aircraft k and l, are following the lead pair (aircraft i and j), enforcing separation between the lead aircraft in the pair and the second of the trailing aircraft is irrelevant. In this case, the triangle inequality holds (i.e., $sep_{jk} + sep_{kl} \geq sep_{jl}$; see Fig. 3).

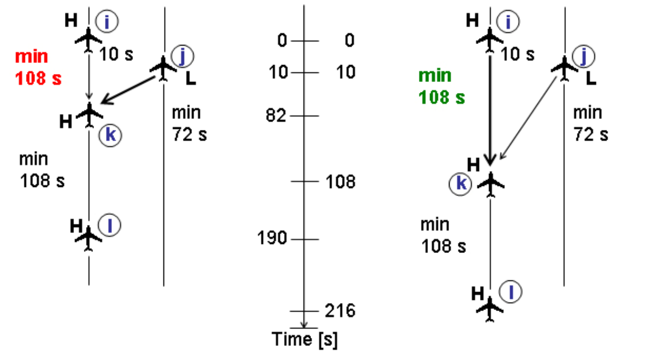


Figure 3. Separation constraint between a pair and its follower.

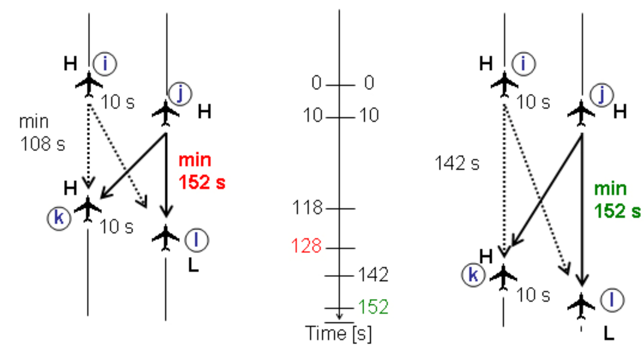


Figure 4. Separation constraint between two pairs.

Considering the risk of blunder of the lead aircraft in a pair, the trailing aircraft needs to provide some minimum separation. Therefore, it will be able to avoid a break-out of the lead. Human test pilots involved in VCSPA simulations [12] indicated that they prefer to operate on the front side of the safe zone rather than being close to the rear boundary. Based on this, a LPB of five seconds was chosen. This separation constraint can be described mathematically as follows:

$$t_j - t_i \geq -(y_{ji} + z_{ji}) \cdot M + (y_{ij} + z_{ij}) \cdot LPB, \quad z_{ji}, y_{ji} \in \{0,1\} \tag{6.2}$$

Similar to the lower bound of the pairing window, an upper bound is also defined. A trailing aircraft in a pair is not allowed to exceed this boundary. Beyond this rear side of the safe zone a high risk of wake encounter exists. Constraint (6.3) enforces a separation for the trailing aircraft to its predecessor such that it is not scheduled beyond the rear boundary of the defined safe zone.

$$t_j - t_i \leq (y_{ij} + z_{ji}) \cdot M + z_{ij} \cdot UPB,\ z_{ji}, y_{ij} \in \{0,1\} \tag{6.3}$$

Route constraints: The arrival of aircraft i at the scheduling point before aircraft j is enforced, if the nominal ETA of aircraft i is earlier than the nominal ETA of aircraft j and if the two aircraft are not paired. The constraint is not enforced if the aircraft are scheduled to be paired.

For all

$$i, j \in (1,...,N),\ i \neq j:\ t_j - t_i \geq -(y_{ij} + z_{ji}) \cdot M, \quad \text{if } r_i = r_j \text{ and if } t_{i,ETA} < t_{j,ETA}. \tag{7}$$

VCSPA grouping constraints: If both aircraft can fly at the same or similar approach speeds, they may be selected to perform a VCSPA. It is important to note that two aircraft of the same type may not be paired if their weights and thus, their desired approach speeds are very different. The TACEC aircraft grouping was used [11]. The constraint can be written as follows:

For all

$$i, j \in (1,...,N),\ i \neq j:\ z_{ij} = 0,\ z_{ji} = 0 \text{ if } g_i \neq g_j. \tag{8}$$

III. Approach and Procedure

For this study, a traffic-set of 20 aircraft was used. The nominal ETAs of these aircraft are randomly distributed over a time period of 30 minutes.

If an aircraft speeds up and/or is assigned a shorter route, it may arrive earlier than its nominal ETA. This is referred to as time advance. The E-ETA for all aircraft is set to 60 seconds prior to the nominal ETA. An even earlier arrival time is usually not desirable due to fuel consumption considerations [13].

A fleet mix of eight heavy aircraft, eight large aircraft and four small aircraft was chosen. The aircraft types were selected based on the wake categories. Using the TACEC aircraft grouping most of the aircraft belong to one VCSPA group and thus, may be paired for VCSPA. Finally, an approach route for each aircraft was chosen arbitrarily.

In order to compare scheduling methods for VCSPA, first, the objective function and constraints were implemented into a CPLEX mixed integer linear program (CPLEX v11.0) using the modeling language OPL (ILOG OPLStudio v5.5). The optimal solutions computed by CPLEX are used foremost as scale for comparison with the results computed using other scheduling methods. For the remainder of this paper scenarios referring to this method use the denotation "CPLEX."

Secondly, the model was coded as a C++ program using the genetic algorithm (GA) library (GAlib). Genetic algorithms cannot guarantee an optimal solution. However, often a solution of high quality can be expected. Moreover, the major advantage of heuristics is the possibility to deliver a feasible solution at any time. For the remainder of this paper scenarios referring to this method use the denotation "GAwoG" (Genetic Algorithm without Greedy).

A third scheduling method is a variation of the C++-program mentioned above. A greedy algorithm was embedded into the genetic algorithm. Each time the GA finds an improved and feasible solution to the problem, the greedy algorithm tries to improve the current best solution by adjusting the separation times between unpaired aircraft. The sequence computed by the GA and also the separation times between paired aircraft are not changed. For the remainder of this paper scenarios referring to this method use the denotation "GAwG" (Genetic Algorithm with Greedy).

These three advanced scheduling methods were compared to two First Come First Served (FCFS) scenarios. One scenario represents a possible schedule under visual meteorological conditions (VMC). Aircraft are paired if they belong to the same VCSPA-group and if the E-ETA of the next aircraft in the sequence is no more than 60 seconds behind the preceding aircraft. The trailing aircraft was scheduled in all pairs five seconds behind its leader.

The second FCFS scenario is the schedule that would be applied under instrument meteorological conditions (IMC). It does not contain any closely spaced pairs, because under IMC current parallel approach operations to closely spaced runways, such as the Simultaneous Offset Instrument Approaches at the San Francisco Airport, cannot be continued and arrivals have to be handled as a one runway-scheduling problem [1]. The FCFS scenarios are used as baseline to which the other three scheduling methods were compared. For the remainder of this paper scenarios referring to FCFS use the denotation "FCFS_VMC" and "FCFS_IMC."

Input into the scheduling algorithms was the E-ETA and L-ETA. For testing the route constraints, the nominal ETA was used. Furthermore, the VCSPA group and the name of the route each aircraft is flying are used as algorithm input. Lastly, the wake category of each aircraft and the wake separation values for each category combination are used as input. Table I shows the separation minima at the coupling point for unpaired aircraft. The times include a buffer (equiv. 5NM) that accounts for compression of the separation distances between the aircraft during the 12 NM flight from the coupling point to the runway. Output of the scheduling algorithms is the STAs at the coupling point for each aircraft in the set.

The independent variables were:

- *Scheduling method* (FCFS_VMC, FCFS_IMC, CPLEX, GAwoG, GAwG).
- *Pairing Time Window (PTW):* The PTW is the time between LPB and UPB. It describes the time span in which an aircraft can be scheduled in respect to a paired, leading aircraft. (cp. constraints (6.2) and (6.3)) As mentioned before, the LPB was set to five seconds. For the UPB three values were chosen: 10, 15 and 20 seconds.

- *ETA window:* For each aircraft the E-ETA is set to 60 seconds prior the nominal ETA. In the different scenarios, for each aircraft the L-ETA is set to a different value for each size of the ETA time window. Adding either 10, 20 or 30 minutes of delay to the nominal ETA, resulted in the following ETA time windows: -60s – 600s, -60s – 1200s, -60s – 1800s.

The combinations of the three independent variables resulted in a simulation matrix with 45 scenarios. For each of the scenarios, makespan, average delay and computation time were measured as dependent variables.

The runtime of the CPLEX program greatly depends on the data input. Data sets, in which the nominal ETAs of the flights are very similar, may cause very long computation times. The GA-programs ran for $1 \cdot 10^5$ iterations which resulted in computation times at least as long as the ones of the CPLEX program.

TABLE I. SEPARATION MINIMA ENFORCED AT THE COUPLING POINT

[s]	Follower				
Leader		Small	Large	B757	Heavy
	Small	98	83	83	72
	Large	147	83	83	72
	B757	180	125	125	108
	Heavy	213	152	152	108

IV. RESULTS

The results of the 45 simulations described the performance of the five scheduling techniques when using different settings for the ETA time window and the pairing time window. Moreover, the potential gain on throughput by using advanced scheduling methods opposed to FCFS method was shown, under the consideration of limitations, such as the absence of uncertainty and the characteristics of the traffic sample.

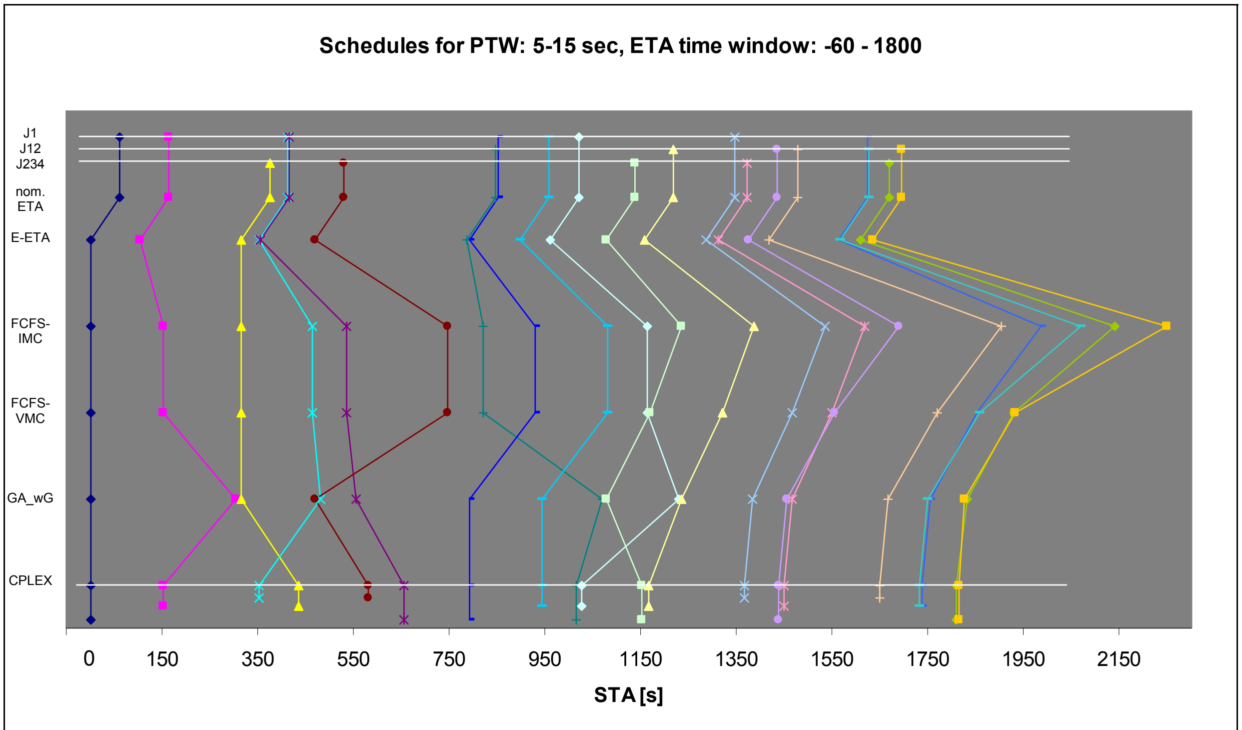
Makespan: When using a traffic-set with a fixed number of aircraft (the static case) makespan is equivalent to throughput. It is important to emphasize that if using makespan as an optimization objective alone, any sufficiently large gap in a schedule renders any aircraft combination before the gap irrelevant. For example, if the E-ETA of the last aircraft is larger than the earliest arrival time allowed, based on separation minima, the sequence of the aircraft ahead of this last one is irrelevant to makespan. CPLEX and the improved genetic algorithm program resulted in solutions with improved makespan compared to FCFS. The comb-diagram in Fig. 5 shows for the scheduling methods researched the differences in makespan as well as changes in the arrival sequence. The diagram shows results for the scenario using a PTW of 5-15 seconds and an ETA time window of -60 – 1800 seconds. The wake categories are shown in the second row of the table below the diagram as Heavy (H), Large (L), and Small (S). Besides the nominal ETA and the E-ETA, results of the two FCFS scheduling methods, the improved GA program and the MILP (FCFS_VMC, FCFS_IMC, GAwG and CPLEX) are shown. Even though no CPS constraint was modeled, no position shift greater than two occurred.

The solutions of the GA programs and the FCFS_VMC method have similar makespan values and are, with respect to the FCFS_IMC scenarios, comparable to the optimal solutions computed by CPLEX. Fig. 6 shows the results for all combinations of scheduling method and pairing time window. The GAwoG scenarios show an average improvement of 14.4% over FCFS_IMC, but only a 0.5% improvement over the FCFS_VMC. The average improvement of the GAwG scenarios over FCFS_IMC is with 17.3% slightly more than the GAwoG scenarios. Compared to FCFS_VMC the improvement is 4%. CPLEX computes solutions with the largest improvement over both FCFS solutions. The solutions are on average 19.23 % better when comparing to FCFS_IMC and 6% better when comparing to FCFS_VMC solutions. The results of the CPLEX-scenarios show that varying the pairing time window has a slight effect on the makespan. Increasing the PTW results in a slight decrease in makespan. Changing the size of the ETA time window however, does not have any effects on the makespan. For the two genetic algorithm programs, no apparent influence on makespan is distinguishable when changing the ETA time window or the pairing time window.

Average Delay: In this study, delay was defined as time deviation from the earliest possible ETA. Because of that, all delay values are positive. Fig. 7 shows average delay for all computed scenarios.

The only independent variable that has a considerable influence on delay is the scheduling method. The data do not support any conclusion that either the size of the ETA time window or the size of the pairing time window affects the amount of delay accumulated.

There are large differences in average delay between the scenarios of the advanced scheduling methods and FCFS_VMC, which allow closely spaced aircraft pairs, and FCFS_IMC. The aircraft of the schedules computed by the basic GA accumulated on average 22% (54 seconds / aircraft) less average delay than the aircraft in the FCFS_IMC, but about 9% (16 seconds / aircraft) more average delay than the FCFS_VMC schedules. The greedy algorithm in the improved GA helps to substantially reduce the delay generated. The aircraft of the schedules of the improved GA program accumulated on average 46% (1:54 minutes / aircraft) less average delay than the FCFS_IMC and 25% (44 seconds / aircraft) less average delay than the FCFS_VMC solution. In the optimal solutions of the scenarios, the aircraft accumulated on average 54% (2:15 minutes / aircraft) less average delay than the FCFS_IMC and 36% (1:05 minutes / aircraft) less delay than in the FCFS_VMC scenarios.



	A/C 1	A/C 2	A/C 3	A/C 4	A/C 5	A/C 6	A/C 7	A/C 8	A/C 9	A/C 10	A/C 11	A/C 12	A/C 13	A/C 14	A/C 15	A/C 16	A/C 17	A/C 18	A/C 19	A/C 20
Wake Cat.	H	L	L	S	H	S	H	H	L	L	H	L	S	L	H	S	L	L	H	H
J1	60	164		412	416			851	957	1022			1345				1623			
J12							848					1218			1436	1477		1627		1696
J234			376			531					1137			1372					1670	
nom. ETA	60	164	376	412	416	531	848	851	957	1022	1137	1218	1345	1372	1436	1477	1623	1627	1670	1696
E-ETA	0	104	316	352	356	471	788	791	897	962	1077	1158	1285	1312	1376	1417	1563	1567	1610	1636
FCFS_IMC	0	152	316	463	535	748	820	928	1080	1163	1235	1387	1534	1617	1689	1902	1985	2068	2140	2248
FCFS_VMC	0	152	316	463	535	748	820	928	1080	1163	1168	1320	1467	1550	1555	1768	1851	1856	1928	1933
GA_wG	0	304	316	482	554	471	1068	791	943	1229	1077	1235	1382	1466	1454	1667	1755	1750	1833	1827
CPLEX	0	152	435	352	654	582	1015	791	943	1026	1152	1167	1365	1448	1437	1650	1738	1733	1810	1816

Figure 5. Nominal ETAs as well as schedules computed using FCFS (VMC and IMC) and advanced scheduling methods.

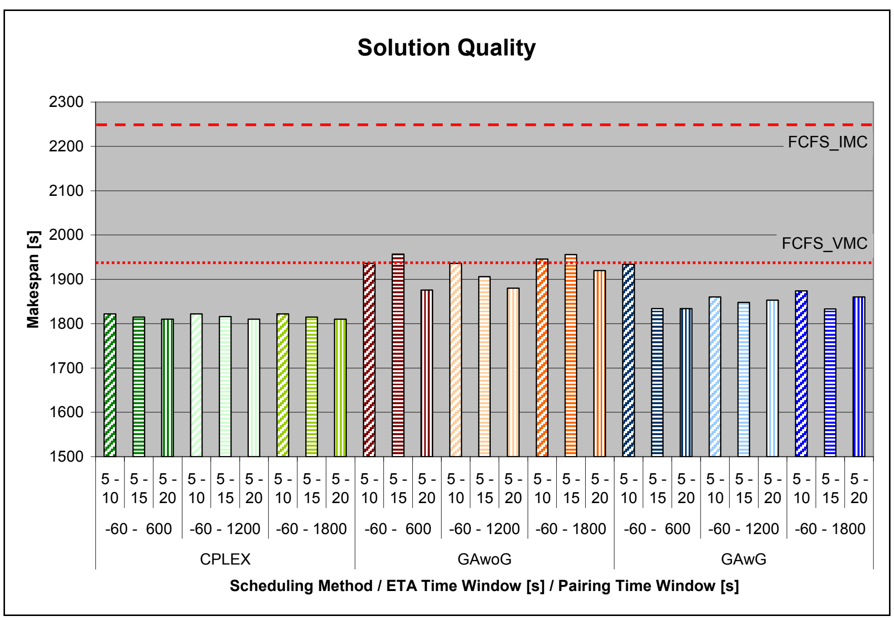


Figure 6. Makespan for all combinations of scheduling method and pairing time window. The sequence and makespan of the FCFS scenarios does not change.

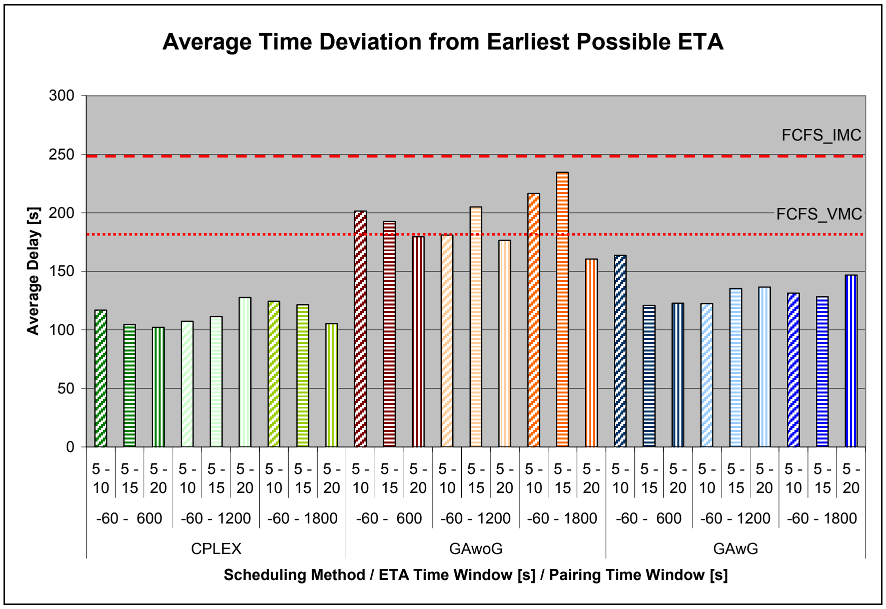


Figure 7. Average delay (deviation from earliest possible ETA). The sequence and the delay of the aircraft in the FCFS scenarios does not change.

Computation Time: In Fig. 8 the computation times of the CPLEX and GA scenarios are plotted. The optimal solutions were computed using a PC laptop with two Intel Core processors, at 2.164 GHz, and 4 GB of memory. The C++ programs ran on a different PC laptop with an Intel Core Duo CPU at 1GHz, and 1GB of memory. As mentioned before, the computation time can greatly vary dependent on the data input. If the aircraft in a set have much smaller inter arrival times and larger ETA time windows, the CPLEX program may require much longer computation times, because of a strongly increased solution space. Both, CPLEX and the GA are sensitive to the number of aircraft in the traffic set.

The FCFS scenarios were computed manually. For that reason results for the computation time are available only for the three advanced scheduling methods. The average computation time for the scenarios computed by the improved GA is slightly less than the average computation time for the standard GA. For the CPLEX program, the three solutions using an ETA time window of -60 – 600 seconds show much shorter computation times than the solutions of the other two ETA time window settings. This behavior cannot be found for the two GA-programs. The results do not show any correlation between the required computation times of each scenario and the variations of the size of the pairing time window. A major difference between the two versions of the GA-programs is that with the use of the greedy improvement algorithm improvements in makespan were achieved very quickly. Already after a very short computation time the solution quality dropped to values close to the optimal solution. The standard GA required more iterations to improve the solution quality.

Average pairing gap: As expected, a larger pairing time window caused in most scenarios the algorithms to use the added flexibility and to schedule trailing aircraft further behind their lead. It is interesting to recognize that in general, trailing aircraft are scheduled well before the rear boundary of the safe zone (Fig. 9).

V. Discussion

In the future, VCSPA are intended to be applicable under all weather conditions at airports with parallel runway systems, with separations as little as 750 ft. The procedure may provide an increase in arrival throughput at airports where a closely spaced parallel runway system is or will be available, or at airports where currently simultaneous arrival operations have to be stopped when weather conditions worsen. Currently, FCFS is the scheduling method that is commonly used by the controllers.

For the envisioned application of VCSPA, this study investigated potential improvements in makespan when applying advanced scheduling algorithms as opposed to FCFS. The performance of heuristics was investigated by comparing arrival schedules computed by two programs using genetic algorithms with the respective optimal schedules, computed using mixed integer linear programming. Also, evaluating computation times was of great importance, considering a possible application in real time simulations. Lastly, this study investigated the extent to which the performance of the algorithms was sensitive to variations in the pairing time window and ETA time window.

Assessing the different scenarios in regards to makespan alone, the advanced scheduling algorithms as well as FCFS_VMC show a clear improvement over FCFS under IMC. This indicates the potential gain on arrival throughput when pairing of aircraft is possible. The CPLEX and the GA solutions do provide improvements of about two minutes in makespan compared to FCFS_VMC. This is a relatively large amount of time for a scheduling period of approximately 30 minutes, allowing for the possibility of scheduling one additional pair of aircraft. The performance of the FCFS_VMC method is similar to the GA programs, as pairing of aircraft is permitted.

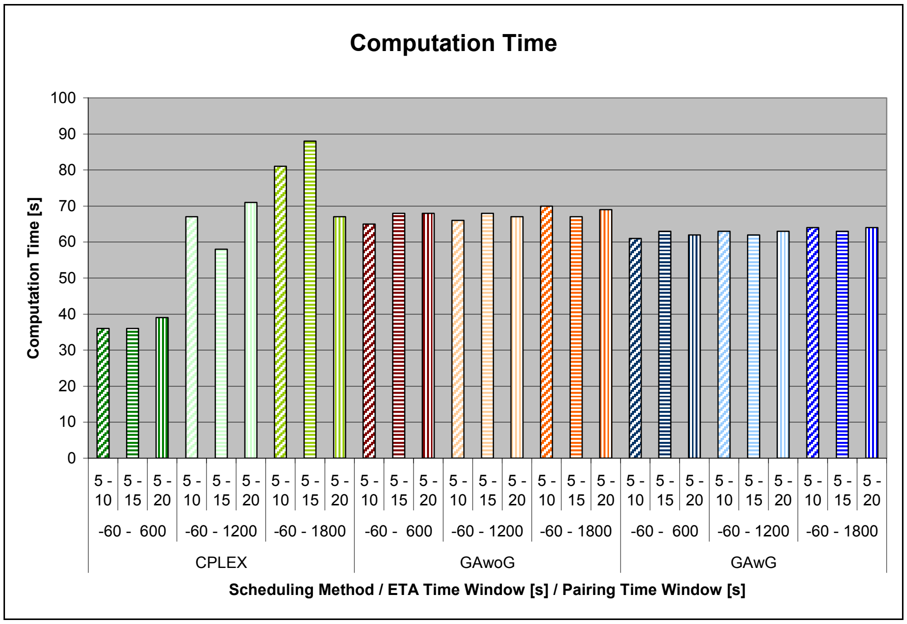


Figure 8. Computation times for the CPLEX and genetic algorithm scenarios. The FCFS scenarios were computed manually.

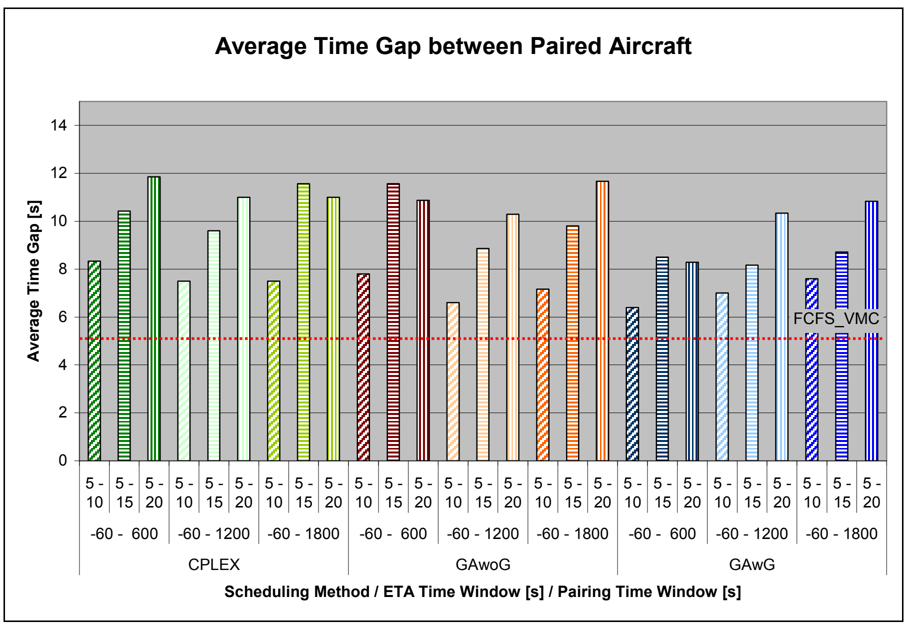


Figure 9. Average time gap between paired aircraft. The FCFS (VMC) sequence and the time gap between paired aircraft does not change.

Unlike the other two independent variables, the size of the ETA time window does not have an effect on makespan. When minimizing makespan, the aircraft are usually scheduled as early as possible. A larger UPB is not a critical limitation.

For the CPLEX scenarios, an increase in the PTW results in a decrease in makespan. Two explanations for this are: first, a larger PTW may allow different VCSPA pairs when compared to a smaller PTW and thus provides of more advantageous aircraft wake category combinations in the pairing. In the example shown in Fig. 10, an UPB of 15s allows only the pairing of the two Heavy aircraft. An UPB of 20 seconds allows also the pairing of the first Heavy and the Large aircraft. Second, similar to the previous case, if the PTW is larger, pairings may be possible that were not possible with a smaller PTW. If in the example shown in Fig. 11 the UPB is 15s the Large aircraft cannot be paired with the second Heavy aircraft (required separation 152s). If the UPB is 20s, pairing is possible. The correlation between the PTW and makespan that was found for the CPLEX scenarios cannot be found for the scenarios computed by the two heuristics. There, the random search for a feasible solution directly impacts the objective value.

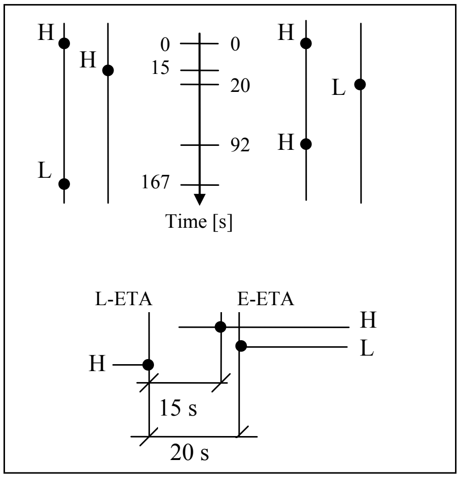


Figure 10. Additional pairing combinations are possible because of an increased pairing time window.

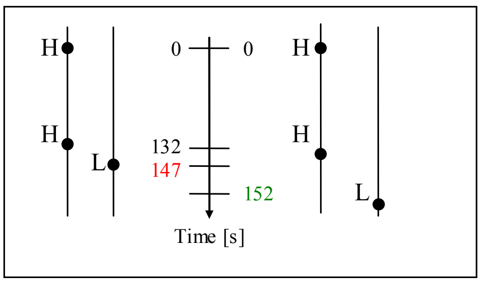


Figure 11. Because of an increased PTW, aircraft pairing may become possible.

The pairing of aircraft provides the possibility to avoid the standard wake separation and thus not only to increase the throughput but also to allow aircraft to arrive closer to their E-ETA. Delay is reduced. When comparing both of the GA programs with the FCFS_VMC, the advantage of the improved GA program becomes obvious. While the basic GA creates on average more delay than FCFS_VMC, the embedded greedy algorithm explicitly helps to reduce delay. Similar to makespan, the advanced scheduling methods and the FCFS_VMC method save a noteworthy amount of delay when compared to FCFS_IMC.

Besides makespan and delay, the computation time is another important measure. A reasonable small computation time is required for real time application. The computation time holds the major advantage of heuristics over computing an optimal schedule using CPLEX. The computation time of a CPLEX program strongly depends on the traffic-set used. The Genetic Algorithm programs, however, belong to so-called any-time-algorithms, meaning that a solution can be made available at all times. The uncertainty of when the optimal solution is available makes the application of CPLEX for the problem of VCSPA scheduling in simulation environments undesirable. Faster methods that compute optimal solutions such as dynamic programming are required.

If the separation of aircraft in a pair increases, it is assumed that an increase of makespan due to separation criteria outweighs the potential reduction of makespan because of additional possible aircraft pairs. According to the results found, the scheduling of the trailing aircraft in a pair well before the rear boundary seems to underpin this assumption. Yet, as described above, in certain cases a larger PTW may enable aircraft to be paired up or it may allow different aircraft (categories) to be paired. This results in a smaller makespan. Further research of this relationship is required.

FCFS is often described as a reliable and robust method frequently applied by controllers. Brentnall [14] points out that besides the arrival rate also the fleet mix is of high importance when comparing advanced scheduling to FCFS scheduling. Only if the fleet-mix is sufficiently varied improvements of advanced sequencing are possible. The findings of the simulations show that the advanced scheduling methods resulted in better schedules compared to the FCFS methods. A more homogeneous traffic set would allow more pairings and thus, smaller makespan values in the FCFS_VMC scenarios. This agrees with the findings of [14].

VI. Summary

VCSPA is a promising concept to significantly increase arrival throughput within the medium to long term time horizon of future airspace systems. Already existing parallel runways may be utilized, or new ones may be added between existing and sufficiently separated parallel runways. Therefore, difficult additional land acquisition can be avoided. Similar arrival concepts are already in operation and can help to develop advanced VCSPA procedures. This study addresses the gaps for VCSPA in existing scheduling research. Considering the special characteristics of this arrival procedure, three research questions have been investigated:

1) Which improvements in solution quality (makespan) and delay are possible when using advanced scheduling methods over first-come-first-serve? It was shown that FCFS, when performed under VMC, as well as the advanced scheduling methods resulted in a substantially better makespan and less delay compared to FCFS under IMC, where the problem of aircraft landings is treated as a single runway problem. The optimal solutions and solutions of the improved genetic algorithm program show a further decrease in makespan compared to FCFS under VMC. Approximately 1½ to two minutes can be gained, which would allow for another aircraft pair to be scheduled.

2) What is the difference in the quality of solutions computed using heuristics, namely genetic algorithms, versus optimal solutions? How much optimality is lost and what are the differences in computation time? The genetic algorithm programs, especially the improved one that includes an embedded greedy algorithm, compute schedules that are similar in makespan and delay compared to optimal solutions. The mixed integer linear program prohibits real time applications as computation times are very sensitive to chnages of the dependent variables. Because of less sensitive computation times and high quality results genetic algorithms are useful for simulation applications. It is worthwhile to further investigate this method for VCSPA scheduling.

3) What is the sensitivity on the dependent variables in respect to the applied scheduling method, pairing time window and ETA time window? It was expected that the solutions computed using genetic algorithms, especially an improved version, have a similar quality (makespan) than the optimal solutions using MILP. Furthermore, an improvement in makespan was expected when increasing the PTW and ETA time window. When minimizing makespan, results indicate that the pairing time window but not the estimated arrival time window has an effect on the dependent variables. Foremost the results computed by CPLEX point out that a larger pairing time window is preferable. It was shown that the widely used FCFS procedure is a simple and effective scheduling method, resulting, in solutions with a reasonable low makespan and delay under VMC.

VII. FUTURE WORK

Makespan is just one of several desirable objective functions to be optimized. Considering the problems of optimizing makespan alone, that were mentioned earlier, average delay, total delay or a weighted sum of delays based for example on relative flight priority, crew criticality, passenger connectivity, critical turnaround times, gate availability, on-time performance, fuel status, or runway preference are other objective functions that are of interest for optimization for VCSPA [15].

For VCSPA, staging and pairing of aircraft and for the actual approach procedure, including wake and blunder avoidance, very precise position and wake information is required. Future work needs to research the impact of uncertainty on an arrival schedule and investigate how a sequence may be affected when an aircraft cannot meet its STA and thus eliminating the planned pairing of two aircraft. Also, other less sensitive methods for computing optimal solutions need to be researched.

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