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The Effect of Pop-Up Flights on the Extended Arrival Manager

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Abstract

To assess the effect of flights departing within the horizon of the extended arrival manager (so-called pop-up flights), fast-time simulations were performed using an arrival manager research model. This model is tailored for operations at Amsterdam Schiphol Airport and integrated in BlueSky, an open-source air traffic management simulator. Simulation results show a significantly negative impact of pop-up flights on extended arrival management, in terms of flight crew and air traffic control task load, sequence stability and delay (cost). This impact could be mitigated by pre-planning pop-up flights prior to departure, using their take-off time estimates. This will, however, only be beneficial when these estimates are sufficiently accurate (better than two minutes). With currently achievable accuracies, it is better to discard these estimates in the context of extended arrival management.

I. Introduction

In Europe, air traffic is concentrated on a relatively limited number of major hub airports. Flights to these airports need to absorb delays prior to landing, as these airports experience short-term capacity-demand imbalances. Inbound traffic is guided from upper airspace en-route sectors towards the destination airport. Delays can be absorbed through speed reductions, vectoring, or by placing aircraft in holding stacks. [1]

To mitigate short-term capacity-demand imbalances, Europe's busiest airports have implemented Arrival Management (AMAN) systems. Because of the decentralized nature of European development of AMAN systems, and the differences in airspace design, there is a large variation in the actual working principles and usage between systems at different airports [2, 3]. What these airports have in common, however, is the desire to have aircraft absorb more of their delays en-route, as this increases operational efficiency. [4]

The involved air navigation service providers are therefore currently examining an increase of the working area of their AMAN systems, referred to as the Extended Arrival Management (E-AMAN) concept. In the remainder of this paper, this will be referred to as a horizon extension. With this increased horizon, delays can be absorbed upstream at higher altitude, resulting in lower fuel burn. Two issues, however, arise with the introduction of an extended AMAN horizon: inaccuracies related to Trajectory Prediction (TP), and the occurrence of pop-up flights [5, 6, 7]. While over the last decades, various studies have been published on analysis and improvement of the TP process (see B. Musialek et al. (2010) for an overview [8]), relatively little research has been done on the occurrence of pop-up traffic. Pop-up flights are flights that depart within the Freeze Horizon (FH) of the AMAN system (this is the horizon within which the arrival sequence is, in principle, fixed), implying that these flights still need to join the arriving traffic stream when the sequence has already been established. As a result, the schedule will need to be revised often, which could seriously

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disrupt the arrival management process. Pop-up flights - also referred to as in-horizon departures - pose one of the most significant operational and technical difficulties [3]. Studies indicate that inaccuracies related to the Estimated Time of Arrival (ETA) are substantially larger when the aircraft has not departed yet (which is the case with in-horizon departures); ETAs for airborne flights, even at large distances from the airport, are significantly more accurate when compared to those of pop-up flights [9, 10]. When compared to TP errors, the negative impact of pop-up flights on the arrival management process is therefore considered substantially larger. Due to the horizon extension of E-AMAN, the number of in-horizon departures will increase. Consequently their negative impact might grow as well. In some AMAN systems, pop-up flights need to be planned in manually by air traffic controllers prior to take-off, based on their estimated take-off time. In other AMAN systems, both in Europe and in the United States, this process is automated: pop-up flights are planned automatically based on their estimated take-off time. Because these estimates are inherently inaccurate, a schedule revision often needs to take place once the pop-up flight departs. This can lead to an unstable planning, and could increase task loads for Air Traffic Control (ATC) and flight crew [2, 3, 11, 12]. Until now, pop-up flights have been seen as a managable issue, given their low occurrence. However, when the AMAN horizon is extended, the number of pop-up flights will increase significantly, making them a more relevant issue, that would need to be addressed in the design of an AMAN system.

The work presented in this paper will therefore examine the effects of pop-up flights on E-AMAN, using fast-time simulations. In addition, mitigating measures are proposed, and are subsequently evaluated in a second set of simulations. The remainder of this paper is structured as follows: Section II describes the AMAN research model. In section III the actual occurrence of pop-up flights is analysed. In section IV and section V the simulation setups are described. The paper ends with a discussion and conclusion on the project outcomes.

II. AMAN Research Model

For the work presented in this paper, an AMAN research model was developed and integrated in BlueSky, an open-source Air Traffic Management (ATM) simulator being developed at Delft University of Technology [13]. This research is focused on the AMAN system of Amsterdam Schiphol Airport (airport code EHAM). The working principles of the AMAN research model are therefore based on those of the Advanced Schiphol Arrival Planner (ASAP); a new AMAN that is currently under deployment. Certain advanced features were omitted or simplified in order to reduce the model's development time.

The basic working principle of ASAP is as follows: once radar data is available, the trajectory predictor (TP) periodically derives an Estimated Time of Arrival (ETA) for that aircraft. In a simulated environment, this trajectory prediction is relatively straightforward, as all contributors to uncertainty are known in advance. Based on the ETAs of all flights, the scheduler sets up a schedule and assigns a Scheduled Time of Arrival (STA) to all applicable aircraft. Delays are supposed to be absorbed prior to the Terminal Maneuvering Area (TMA) entry, hence STAs are translated to Expected Approach Times (EATs) at the Initial Approach Fix (IAF). In practice, this means that en-route controllers (Area Control) should pro-actively manage the aircraft such that they can be handed over to approach controllers at the IAF around around this expected time.

Each of these aspects corresponds to a specific horizon within the AMAN system, see Figure 1. The research model periodically derives the ETAs for all aircraft within the AMAN Eligibility Horizon (EH), i.e., the horizon from which radar data is available. TP inaccuracies have been reduced pro-actively to a minimum, since these errors might otherwise confound the effects of pop-up occurrence.

The ASAP scheduler gathers the ETAs for all applicable flights, sets up a plan, and assigns STAs. For aircraft outside the AMAN Freeze Horizon (FH), which is typically substantially smaller than the EH, the schedule and corresponding STAs are updated and revised continuously using a First Come First Served (FCFS) algorithm. Once flights enter the FH, their STA is in principle fixed, unless a pop-up flight departs and triggers a schedule revision. Pop-up flights are those aircraft that depart within the FH, and possibly impose STA revisions to (multiple) airborne flights. In the framework of AMAN and E-AMAN, the FH is set to 120 nm and 200 nm respectively in the model [7, 14]. In the scheduler, pop-up flights are only considered once airborne and integrated in the sequence, as is currently the case for most European AMANs.

This implies that only airborne flights are planned and scheduled. In Simulation Study I (see section IV), this scheduler principle is used. During the research, it was also assessed whether pre-planning pop-up flights before departure could mitigate their negative effect. Based on their estimated take-off time, pop-up flights

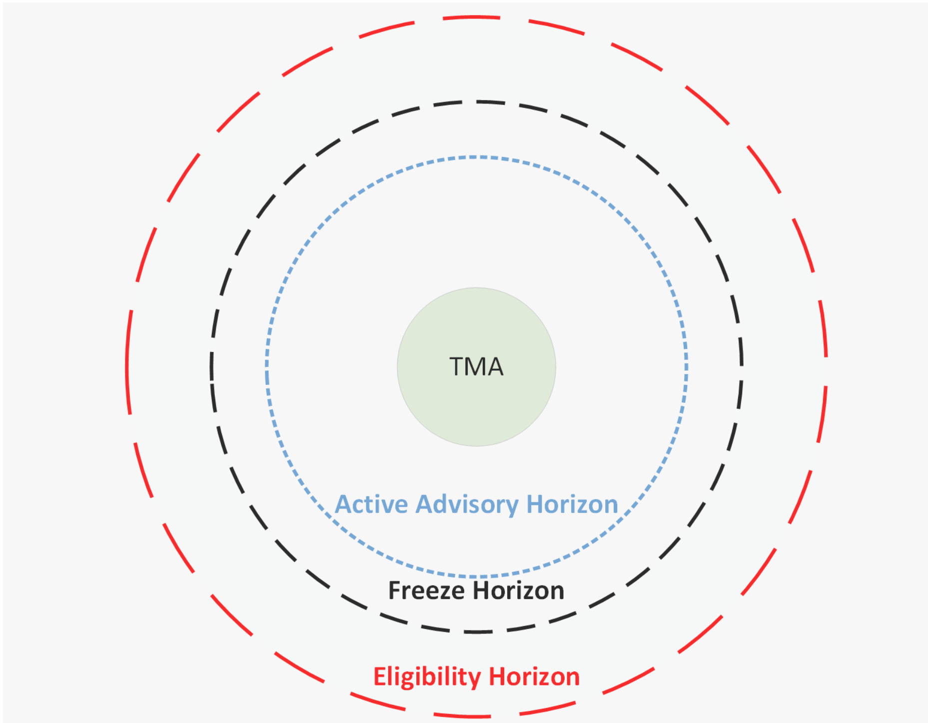

Figure 1. AMAN horizon definitions.

are planned along with the airborne flights, before they actually depart. When the pop-up flight departs, a schedule revision is triggered to finally integrate the aircraft in the sequence. If the pop-up flight departs around its estimated take-off time, the impact of this schedule revision on other airborne flights is relatively small. However, when there is a large discrepancy between scheduled and actual take-off time, the impact on other fights can be larger. In Simulation Study II (see section V), this alternative scheduler is used to assess how accurate the take-off time estimates of pop-up flights should be in order to be useful for pre-planning purposes. It was chosen to integrate the pop-up flights in the sequence, and thereby potentially hinder airborne flights, rather than, for example, systematically delaying those flights until the sequence allows them, as this is considered most desirable and representative for current operations. Pop-up flights are often needed to feed hub-and-spoke systems, hence integrating them in the sequence, rather than systematically delaying them, is crucial.

In ASAP, Area Control is responsible for delivering aircraft at the IAF around their EAT (margin of ±30 seconds). Once aircraft enter the Active Advisory Horizon (AAH), which is typically slightly smaller than the FH, Area Control can provide commands in order to match the desired arrival time. To assist controllers in generating the necessary advisories that deliver the aircraft within the tight time constraints, the Speed and Route Advisor (SARA) tool has been integrated in ASAP [2]. A simplified SARA module was developed for the AMAN research model, which automatically generates flight-plan revisions to deliver aircraft around the EAT at the IAF. Speed advisories can be provided by means of reducing the speed of the aircraft up to 10% over the remaining trajectory. Route advisories are provided when the delays are too large to be absorbed with speed reductions only. This route advisory generation process has been simplified by means of concentrating the advisories on the last leg prior to the TMA entry. Depending on the magnitude of the delays to be absorbed, aircraft are vectored or placed in so-called holding stacks.

III. Pop-Up Occurrence

Prior to the fast-time simulations, the occurrence of pop-up flights was analysed to provide an indication on the possible disturbances induced. To broaden the analysis, five of Europe's busiest airports were assessed. Enhanced Tactical Flow Management System (ETFMS) data for three days were extracted using

Eurocontrol's Network Strategic Tool (NEST) [15], to be processed and analysed. The pop-up occurrence results are shown in Table 1, both in the framework of AMAN and E-AMAN. For brevity, data for the three test days have been combined and averaged. In the context of AMAN, the occurrence of pop-up flights is

Table 1. Pop-Up Occurrence Results †

Airport		Pop-Up Ratio * AMAN	Pop-Up Ratio * E-AMAN
EHAM	Amsterdam Schiphol	1.8%	10.8%
EDDF	Frankfurt	3.4%	15.0%
EGLL	Heathrow	0.0%	5.5%
LFPG	Paris CDG	0.1%	4.9%
EDDM	Munich	1.7%	14.8%

† Freeze horizon at 120 nm and 200 nm, for AMAN and E-AMAN respectively

* Ratio expressed as percentage of all arrivals

not significant. As the horizon is extended (E-AMAN), the occurrence of pop-up flights increases. When comparing the various airports, it is clear that there is a large difference when comparing Heathrow and Paris Charles de Gaulle airport on one hand, to Frankfurt and Munich airport on the other hand. Due to the type of flights accommodated, it can be seen that certain airports are significantly more impacted due to the occurrence of pop-up flights. This also validates the decision to focus this research on one airport. Although the pop-up ratio for Schiphol in E-AMAN is - on average - 10.8% over the full day, ratios up to 30% per rolling half hour were recorded, even during inbound peak periods. It can therefore be concluded that the occurrence of pop-up flights is relatively large, and therefore the actual effects might be too. In the next section, the impact of pop-up flights on AMAN and E-AMAN is assessed.

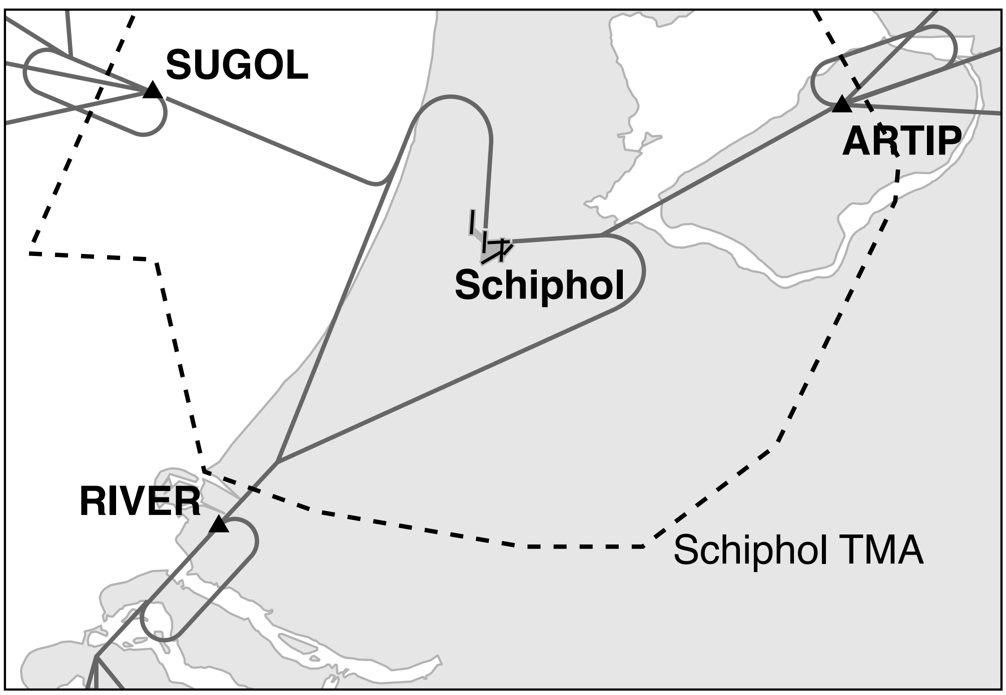

Figure 2. Approach routes in simulation.

IV. Simulation Study I: The effect of pop-up flights

A simulation study was performed to assess how pop-up flights impact the (extended) arrival management process, by observing several ratios of pop-up flights in the samples. In addition, the implications of a horizon extension from AMAN to E-AMAN were assessed.

A. Simulation Set-Up

1. Apparatus and Model

To assess the effect of pop-up flights, simulations were performed using BlueSky [13], with the AMAN research model presented in Section II. Simulations were carried out in fast-time, where controllers were assumed to always follow the SARA advisories presented in Section II. Conflict detection and resolution functions were disabled, as they could interfere with the arrival management process. In reality, ATC uses AMAN systems as a complementary tool, and performs the tactical functions simultaneously. All simulations were performed for Amsterdam Schiphol Airport, see Figure 2. Runways 18C and 27 were used for arrivals, each with a landing interval of 100 seconds. Based on the IAF in the flight plan, runways were allocated during the scenario generation process. Here, the SUGOL IAF fed runway 18C, ARTIP fed runway 27, and RIVER fed both randomly. Although in reality prediction uncertainties will affect the arrival sequence, these were not considered (or modeled) in the current setup.

2. Independent Variables

This simulation study investigates the effect of pop-up flights on arrival management for both the existing AMAN, and the envisioned E-AMAN systems. The AMAN *Freeze Horizon* (FH) is therefore an independent variable with two levels: FH could be either 120 (AMAN), or 200 nautical miles (E-AMAN). *Pop-up Scaling* (PS) is defined as the scaling of the relative occurrence of pop-up flights in percent. If PS is 100%, pop-up flights occur as in the original sample (for the applicable horizon). For smaller and larger PS, pop-up flights were replaced by longer-haul flights (or vice versa). By doing so, the actual traffic demand remains similar and the outcomes of the conditions can be compared. In the simulation study, pop-up scaling is an independent variable with three levels; respectively $PS = 0\%$, $PS = 100\%$, and $PS = 200\%$. The conditions are summarized in Table 2.

Table 2. Conditions[†] for Simulation Study I

Simulation Condition	AMAN FH	Pop-Up Scaling
A/0		0%
A/100	120 nm	100%
A/200		200%
E/0		0%
E/100	200 nm	100%
E/200		200%

[†] The first and last three conditions correspond to the AMAN and E-AMAN context, respectively.

3. Analysis Design and Traffic Samples

The analysis was designed as a within-subjects, repeated-measures, where several conditions were compared using twelve different traffic samples. In other words, each test condition was simulated with the same twelve traffic samples. These samples consist of ETFMS flight plan data[a] for a given time window, complemented with ASAP's TMA routes (section II). If the occurrence of pop-up flights was altered by replacing pop-up flights with longer-haul flights (or vice versa), items in the original sample were modified. The traffic samples were based on six weekdays in the summer of 2015, from which two fixed peak period arrival periods (each lasting three hours) were used. The six test days were selected semi-randomly from the pool of busiest days: per summer month (July, August, September), two weekdays were chosen. For each day, the same two fixed peak periods (busiest moments of the day) were selected. Hence, busy periods of inbound traffic

[a]Called M2 trajectories in the Eurocontrol Demand Data Repository.

were simulated, as arrival managers are considered most useful in these situations. The number of arrivals to EHAM in the selected samples is shown in Table 3.

Table 3. Traffic Samples

Sample	# 1	# 2	# 3	# 4	# 5	# 6
Arrivals	135	142	132	138	130	145
Sample	# 7	# 8	# 9	# 10	# 11	# 12
Arrivals	128	143	135	140	144	136

4. Dependent Measures

The overall performance of the (extended) arrival management process was evaluated in terms of delay (cost), runway capacity, sequence stability, and task load of flight crew and air traffic control. *Delay (cost)* was measured in two ways: both in terms of the average required delay absorption at low altitude[b] (in seconds), and in terms of the average energy cost caused by absorbing airborne delays, normalized by flight-plan distance (in mega-Joule per nautical mile, MJ/nm). Here, energy was calculated as the product of thrust and velocity, integrated over time. This was used instead of fuel burn, to avoid having to rely on inaccurate fuel models.

Runway capacity was measured using the average runway inter-arrival time on runways 18C and 27. The number of Scheduled Time of Arrival (STA) revisions per run, and the number of disturbed descents per run were used as measures of *task load*. Here, a descent was considered disturbed when the STA of an aircraft is revised after its Top of Descent (ToD). Finally, the number of arrival sequence position changes per run was used to assess *sequence stability*. For example, if an aircraft is moved back one position in the sequence as a result of an STA revision, two postion changes are counted: the revised aircraft moving back one position, and the next aircraft moving one position ahead as a result.

B. Hypotheses

Pop-up flights are expected to disturb the extended arrival management (E-AMAN) process. It is therefore hypothesized that a higher occurrence of pop-up flights negatively affects the following dependent measures: delay (cost) (hypothesis 1-1), runway capacity (hypothesis 1-2), sequence stability (hypothesis 1-3), flight crew and ATC task load (hypothesis 1-4). As pop-up flights occur significantly less frequently within the AMAN horizon, it is hypothesized that the negative effect of pop-up scaling is smaller for AMAN compared to E-AMAN (hypothesis 1-5). Moving from AMAN to E-AMAN for actual pop-up occurrence levels is hypothesized to have a positive impact on delay (cost) (hypothesis 1-6). However it is hypothesized to have a negative effect on runway capacity as more delays are absorbed upstream [16] (hypothesis 1-7), on sequence stability (hypothesis 1-8), and on task loads (hypothesis 1-9).

C. Results

Even though all samples are relatively similar in terms of overall traffic demand, the simulation outcomes deviate substantially from sample to sample within a given condition. This can be attributed to the fact that the actual demand evolution is different in every sample. In addition, the effect of pop-up flights might be larger or smaller in a particular sample, depending on when and where the pop-up flights departed. For these reasons, statistical analyses were carried out using normalized and standardized Z-scores[c]. The downside of using Z-scores is that since variables are normalized, information on the magnitude is lost. Because of this, the magnitude of each effect was averaged per condition, and presented in Table 4 to supplement the normalized Z-scores shown in Figures 3-8.

Shapiro-Wilk [17] normality tests indicated that the majority of the Z-score distributions were not normally distributed. Therefore, only non-parametric tests (suitable for a repeated measures design) were used for statistical analysis. Pop-up scaling was considered as a main effect for the AMAN and E-AMAN case

[b]Low-altitude delay is the delay that still needs to be absorbed when an aircraft nears the TMA. This corresponds to altitudes in the range of 9,000 ft - 15,000 ft.

[c]For example, calculating a Z-score for measure 'A' means that for each sample of 'A' in each test condition you subtract the mean of that sample for all conditions, and divide the result by the standard deviation of that sample for all conditions. This way, you maintain the variation between *conditions*, but reduce the interference of the variation between *samples*.

separately, using Friedman's Analysis of Variance (ANOVA) test [17]. Effects were considered significant for $p \leq 0.05$. Post-hoc tests were performed using a Wilcoxon's Signed Rank test [17]. Both for the AMAN and the E-AMAN case, two post-hoc tests were performed, which compared the nominal condition ($PS = 100\%$) to $PS = 0\%$ and $PS = 200\%$, respectively. In addition, the effect of a horizon extension was considered at normal pop-up scaling (A/100 and E/100). With five pairs in total, a Bonferroni correction[d] of 5 is used. Hence, post-hoc tests were considered significant when $p \leq 0.01$.

Table 4. Simulation Study I: Sample averages.

Dependent variable	Simulation condition					
	A/0	A/100	A/200	E/0	E/100	E/200
Average Low-altitude Delay Absorption [s]	141.28	140.95	141.12	119.12	116.10	117.71
Delay energy cost [MJ/nm]	27.41	27.53	27.83	20.74	21.52	23.68
Runway inter-arrival time [s]	123.51	123.54	123.56	124.87	124.71	124.61
Position changes	2.08	6.33	10.08	26.17	40.83	70.83
STA revisions	0.67	0.92	1.75	8.92	24.83	43.50
Disturbed descents	12.08	12.08	12.42	0.17	0.75	1.58

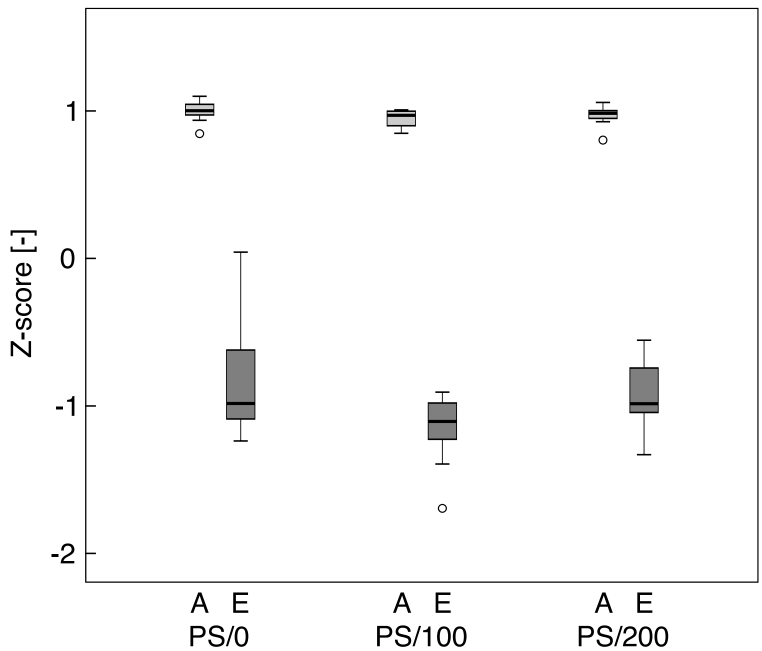

Figure 3. Average low-altitude delay absorption.

1. *Delay (Cost)*

Figure 3 shows the results for the average low-altitude delay absorption. In this and following figures, the thick horizontal lines indicate the median, the grey boxes correspond to the second and third quartile, and the whiskers indicate the first and fourth quartile. When present in the data, outliers are indicated with circles. For both AMAN and E-AMAN, no clear effect of pop-up scaling can be seen. A main effects test also revealed no significant effects of pop-up scaling ($\chi^2(2) = 2.00, p = 0.37$). Runways have a given capacity, based on the inter-arrival time. When the demand nears or exceeds capacity, aircraft need to absorb the necessary delays. The occurrence of pop-up flights does not alter the ratio between demand and capacity. It therefore makes sense that the required degree of low-altitude delay absorption is not affected by pop-up scaling.

A post-hoc comparison of condition E/0 and E/100 revealed that significantly fewer aircraft required low-altitude delay absorption in the E/100 case ($z = 2.98, p = 0.003$). This seems counter-intuitive, however,

[d] A Bonferroni correction is necessary when multiple comparisons are done on one data set, to reduce the chance of reporting a false positive effect [17]. With this correction you divide the significance threshold with the number of post-hoc tests.

it can be argued that schedule revisions are beneficial in this perspective. When re-scheduling aircraft as they are closer to the runway, trajectory prediction (TP) errors are reduced, and the (new) schedule is set up using fewer uncertainties. In reality, TP errors significantly affect AMAN efficiency; these TP errors have been reduced substantially in the research model, however they could not be eliminated. When doubling the pop-up occurrence (E/200) with respect to E/100, no significant effect of pop-up scaling was identified ($z = 1.58, p = 0.11$).

The occurrence of pop-up flights is therefore, to some extent, beneficial in terms of reducing the number of aircraft that require delay absorption. On average, 7% fewer flights require delay absorption when comparing E/100 to E/0, see Table 4. However, when pop-up scaling is increased (E/200), there is no additional benefit when compared to E/100. For AMAN, none of the post-hoc tests revealed a significant difference. This is attributed to the fact that the occurrence of pop-up flights (on average 1.9% in A/100) is too small to observe certain effects. In addition, due to this low occurrence in AMAN, the actual magnitude of the effects is small. Because of this, the remainder of the analysis in this paper will focus primarily on the context of E-AMAN.

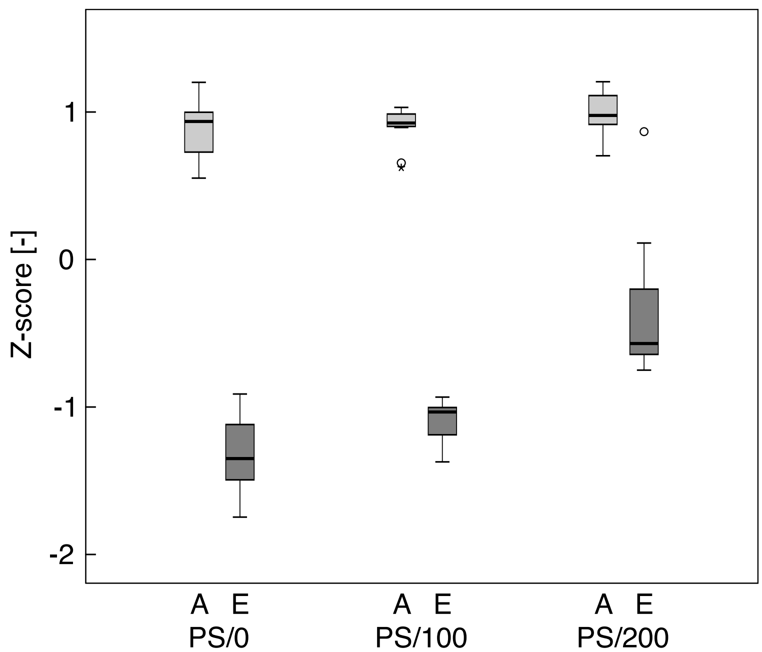

Figure 4. Delay energy cost.

The delay energy cost results are presented in Figure 4. It can be seen that the delay energy cost increases with increasing pop-up scaling. This effect is significant for E-AMAN ($\chi^2(2) = 19.50, p < 0.001$). Post-hoc tests revealed that E/200 differs significantly from E/100 ($z = 3.06, p = 0.002$), where cost is 10% larger on average in E/200, see also Table 4. While post-hoc tests did not indicate a significant difference between E/100 and E/0 ($z = 1.80, p = 0.07$), there is a tendency of increased cost for larger pop-up occurrences, as shown in Figure 4. The overall trend that can be observed from the results, however, is that the larger the uncertainties are, as induced by the pop-up flights, the higher their negative effect on energy cost. Similar to the required delay absorption results, no significant effects were found for pop-up scaling in the AMAN case.

As the horizon is extended, more delays can be absorbed by en-route speed reduction. The disturbances, induced by the increased number of pop-up flights in E-AMAN, are outweighed by the benefits of increased delay absorption. By comparing E/100 with A/100, the average low-altitude delay absorption can be reduced by 17%; post-hoc tests indicate that this result is significant ($z = 3.06, p = 0.002$). As more delays can be absorbed en-route, 26% fewer aircraft require low-altitude delay absorption ($z = 3.06, p = 0.002$, comparing E/100 to A/100). In this comparison, delay energy cost is reduced by 22% due to the extended horizon. This difference is also significant ($z = 3.06, p = 0.002$). These are averaged results, implying that the actual effect magnitude varied depending on the sample. Nevertheless, comparable trends were observed for all traffic samples.

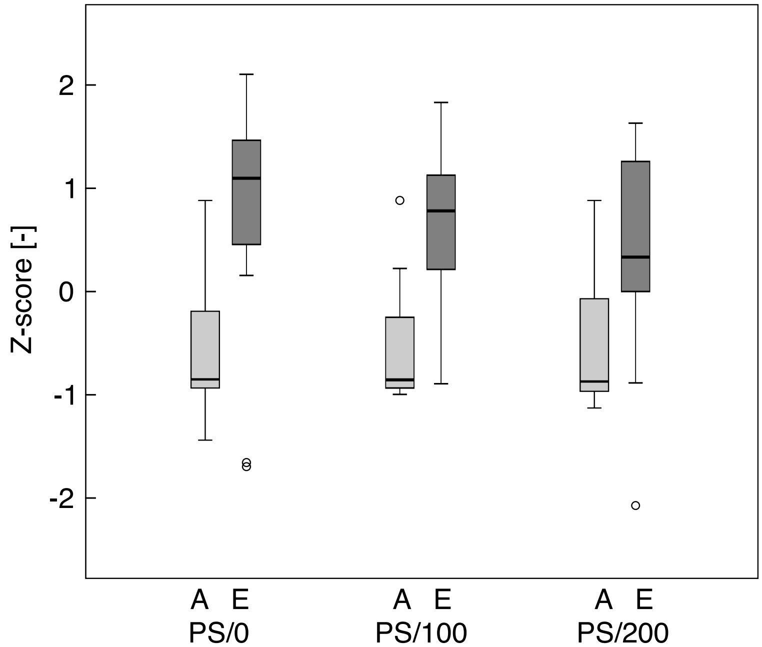

Figure 5. Average runway inter-arrival time.

2. Runway Capacity

Figure 5 shows runway capacity in terms of inter-arrival time, averaged for both landing runways. It can be seen that runway inter-arrival results are similar, irrespective of either pop-up scaling or planning horizon. Indeed, a main effects test did not reveal a significant influence of pop-up scaling in the E-AMAN conditions ($\chi^2(2) = 0.50, p = 0.78$). Similarly, a post-hoc comparison of conditions A/100 and E/100 did not reveal a significant difference ($z = 2.43, p = 0.02$).

3. Sequence Stability

The results in terms of position changes, an indicator for sequence stability, are shown in Figure 6. Here it can be seen that both the increased pop-up scaling, as well as the increased planning horizon, result in an increased number of position changes. A main effects test revealed that the influence of pop-up scaling is significant in the E-AMAN conditions ($\chi^2(2) = 22.17, p < 0.001$). Post-hoc tests showed that E/100 differs significantly from E/0 ($z = 2.82, p = 0.005$), and that E/200 differs significantly from E/100 ($z = 3.06, p = 0.002$). The sample averages of the three E-AMAN conditions (Table 4) indicate that this effect is large: with respect to E/0, the required number of position changes in E/100 increases by 56% on average. When comparing E/200 with E/100, this is increased by an additional 75%. The absolute values show the large negative impact of pop-up occurrence on sequence stability experienced in the context of E-AMAN. Similar statistical results were found in the framework of AMAN, although the actual negative effect is negligible due to the low pop-up occurrence in all AMAN conditions.

Post-hoc analysis also showed that the effect of the increased planning horizon is significant, when comparing conditions A/100 and E/100 ($z = 3.06, p = 0.002$). On average, the required number of position changes is 6 times larger in E/100 when compared to A/100, see Table 4.

For both conditions in which there are no pop-up flights (i.e. A/0 and E/0), the average number of position changes is larger than 0 (see Table 4). This seems counter-intuitive, as all pop-up flight uncertainties are eliminated. However, there are two main reasons why there are still position changes. Firstly, although TP errors were reduced to a minimum, they could not be fully eliminated. As a result, there are still uncertainties in the planning, which might result in sequence changes. Secondly, due to the airspace structure and organisation, aircraft just outside the horizon might interact with aircraft within the horizon. Re-scheduling could therefore be triggered, resulting in sequence changes, even though there are no pop-up flights.

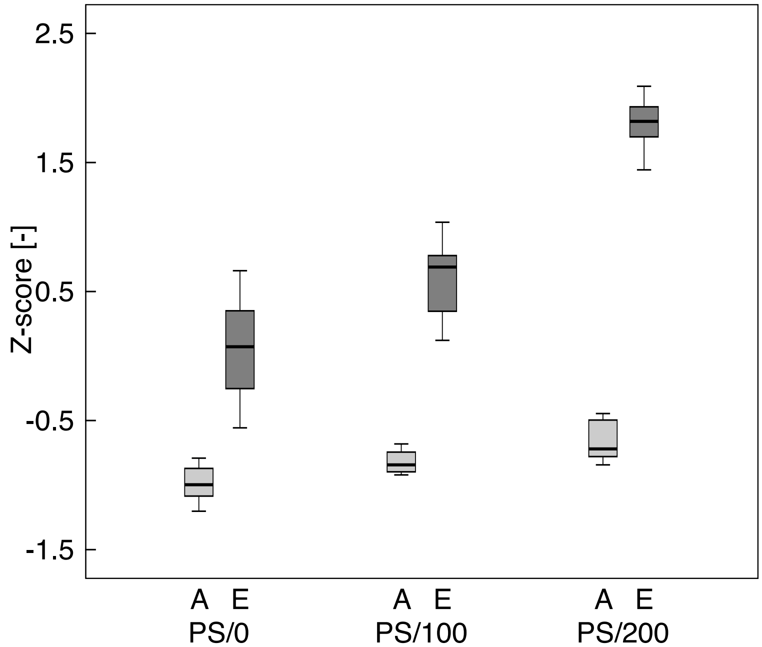

Figure 6. Arrival sequence position changes.

4. Flight Crew and ATC Task Load

Figure 7 shows the results in terms of the number of STA revisions. Similar to the previous metric, it can be seen that increased pop-up scaling has a negative effect on the required number of STA revisions, which is significant for both AMAN ($\chi^2(2) = 13.00, p = 0.01$), and E-AMAN ($\chi^2(2) = 24.00, p < 0.001$). Post-hoc tests showed a significant difference between E/0 and E/100 ($z = 3.06, p = 0.002$), and between E/0 and E/200 ($z = 3.06, p = 0.002$). The disturbances grow as the pop-up occurrence increases. Between conditions E/0 and E/100, both variables increase by nearly factor 3; in E/200, on average 75% more STA revisions occur when compared to E/100. Both in relative and absolute terms, these effects are large. It should be realized that the occurrence of pop-up flights increases from 11.5% (E/100) to 23.0% (E/200). For AMAN, post-hoc tests did not reveal significant differences between pairs, which can be attributed to the low occurrence of pop-up flights with AMAN. The results in terms of the number of disturbed descents are shown in Figure 8. It can be seen that the difference between AMAN and E-AMAN is large, and that pop-up scaling has a smaller negative effect on the number of disturbed descents. A main effects test revealed that the effect of pop-up scaling is significant for E-AMAN ($\chi^2(2) = 10.30$, $p = 0.006$), but not for AMAN ($\chi^2(2) = 2.85, p = 0.24$). Post-hoc tests of the E-AMAN results, however, did not reveal significance between pairs. Nevertheless, Figure 8 does show a tendency of more disturbed descents for increased pop-up occurrence. The sample averages are close to zero for all conditions (Table 4), implying that the effect, even if it would be significant, is very small. While this may seem counter-intuitive, it can be explained by the fact that most pop-up aircraft depart prior to the Top of Descent (ToD) of airborne aircraft. Airborne aircraft therefore rarely experience disturbed descents due to the occurrence of pop-up flights.

Post-hoc comparisons of A/100 and E/100 showed that the effects of the horizon extension are significant both for the number of STA revisions ($z = 3.06, p = 0.002$), and for the number of disturbed descents ($z = 3.06, p = 0.002$). In Table 4 it can be seen that the number of STA revisions is, on average, 27 times larger with E-AMAN. This is caused by the higher pop-up occurrence, which is, on average, 6 times higher in E/100. The number of disturbed descents is reduced to nearly zero in E/100, whereas its occurrence (9% on average) in AMAN is not considered problematic either.

For both conditions in which there are no pop-up flights (i.e. A/0 and E/0), the average number of STA revisions is larger than 0 (see Table 4). As explained before, this is attributed to the fact that TP errors could not be fully eliminated. In addition, due to the airspace structure and organisation, aircraft just outside the horizon might interact with aircraft within the horizon. As a result, STA revisions might also occur if there are no pop-up flights.

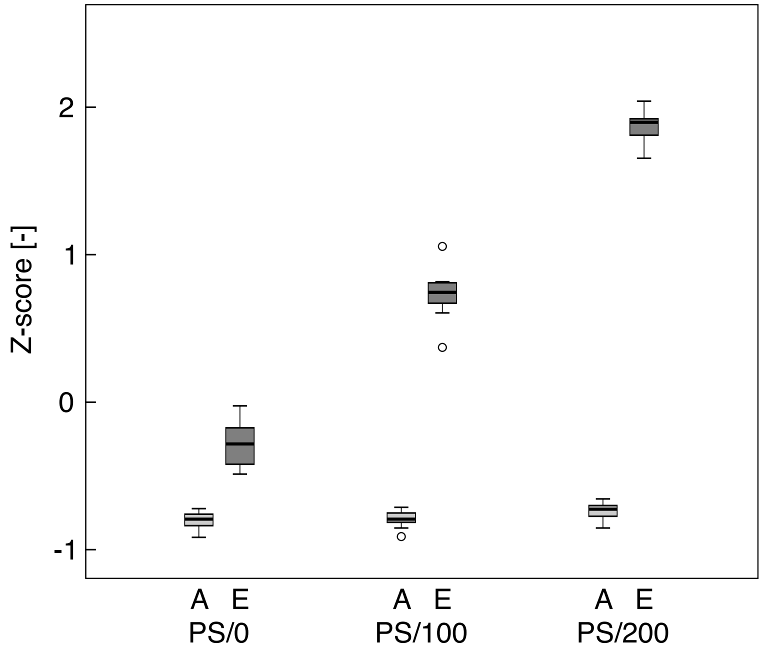

Figure 7. STA revisions.

V. Simulation Study II: Alternative Scheduler

The results of the first study show that pop-up flights negatively affect the (extended) arrival management process. This effect might be mitigated by taking pop-up flights into account, prior to their departure. A second study was therefore performed to assess the benefit of pre-planning pop-up flights prior to their departure. This study evaluated an alternative scheduler that takes this into account, for various levels of accuracy of the departure time estimate.

A. Simulation Set-Up

1. Apparatus and Model

Similar to the first study, fast-time simulations were performed with the AMAN research model. All runs simulated arrivals to EHAM, using the landing interval and runway allocation procedure as applied previously. Compared to the previous study, this set of simulations considers only the extended AMAN horizon, with pop-up occurrence as in current traffic (PS 100%). To ensure that conditions are comparable, departure information accuracy of all pop-up flights was constant within each simulation run.

2. Independent Variables

To assess the effect of pre-planning pop-up flights prior to departure, an alternative scheduler was used that takes this into account. This scheduler explicitly uses the pre-departure take-off time estimates of pop-up flights to plan them along with the airborne aircraft. When a pop-up flight departs at its estimated time, no substantial schedule revisions are required. However, if the pop-up flights departs earlier or later, its reserved place in the sequence needs to be revised once the aircraft gets airborne, possibly impacting airborne aircraft. *Pre-planning* was therefore an independent variable, with five levels: pre-planning could be either absent (i.e., the original scheduler is used, corresponding to condition E/100 in Simulation Study I), or pre-planning was applied with departure estimate errors U/0 (pop-up aircraft departs exactly at its estimated time), U/120 (departs 2 minutes later), U/180 (departs 3 minutes later) and U/300 (departs 5 minutes later). The conditions are summarized in Table 5. When adding uncertainty to the estimated take-off time, a fixed error (of 2, 3 or 5 minutes) was introduced to all pop-up flights in the given condition. While the extended arrival manager pre-planned the pop-up flights using the given estimated take-off times,

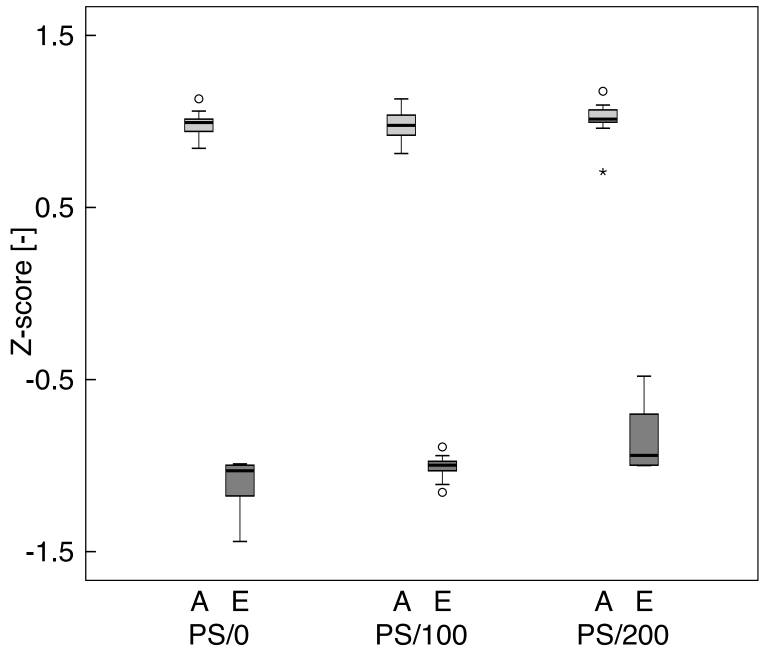

Figure 8. Disturbed descents.

the aircraft actually departed a few minutes later. Rather than introducing a random error to the estimated take-off time, it was decided to add fixed errors, as an indication of the worst-case scenario.

Table 5. Conditions for Simulation Study II

Simulation Condition	Scheduler	Dep. Uncertainty
Baseline	no pre-planning	NA†
U/0	pre-planning	0 s
U/120		120 s
U/180		180 s
U/300		300 s

† Not applicable, as the baseline scheduler does not pre-plan pop-up flights prior to departure.

3. Analysis Design and Dependent Measures

Similar to the first study, the second analysis was designed as a within-subjects, repeated measures. The same traffic samples were used to compare conditions. Also the same dependent measures were used to assess the effect of pre-planning.

B. Hypotheses

It is hypothesized that the pre-planning scheduler outperforms the baseline scheduler when the take-off time estimates are perfect (hypothesis 2-1). In a previous study, Barnier and Allignol found that for aircraft deconfliction, incorporating flights prior to departure was not effective with departure time uncertainties of three minutes [18]. It was therefore hypothesized that for pre-planning of pop-up flights to be effective, the departure time uncertainty needs to be smaller than three minutes (hypothesis 2-2).

C. Results

The statistical analysis process is similar to Simulation Study I. Z-scores were used to assess the results. Similar to the first simulation study, the magnitude of each effect was averaged per condition, and presented in Table 6 to supplement the normalized Z-scores shown in Figures 9-14. Shapiro-Wilk normality tests on the data revealed that for the majority of the data, normality could not be assumed. Friedman's ANOVA was therefore used to evaluate the main effects, where effects are considered significant for $p \leq 0.05$. The Wilcoxon's Signed Rank test was used as a post-hoc test for five pairs: the baseline condition compared to the other four conditions, and U/0 compared to U/120. Using a Bonferroni correction of 5, post-hoc tests are considered significant for $p \leq 0.01$.

Table 6. Simulation Study II: Sample averages.

Dependent variable	Simulation condition				
	Baseline	U/0	U/120	U/180	U/300
Average low-altitude delay absorption [s]	116.1	116.0	121.5	128.1	128.9
Delay e. c. [MJ/nm]	21.5	21.4	22.0	22.3	22.4
Runway inter-arrival time [s]	124.7	124.8	124.7	124.6	124.4
Position changes	40.8	48.1	61.00	61.5	73.1
STA revisions	24.8	15.3	27.8	31.1	36.2
Disturbed descents	0.8	0.8	1.7	2.0	3.1

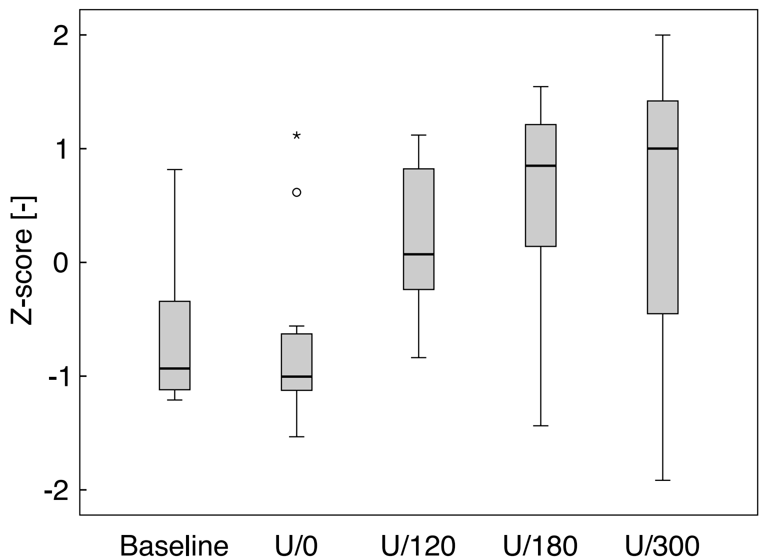

Figure 9. Average low-altitude delay absorption.

1. *Delay (Cost)*

Figure 9 shows the results in terms of low-altitude delay absorption. A main effects test revealed a significant effect of pre-planning ($\chi^2(4) = 13.93, p = 0.008$). Post-hoc tests revealed that scheduling pop-up flights with perfect accuracy does not affect the average low-altitude delay absorption, as condition U/0 does not differ significantly from the baseline ($z = 0.00, p = 1.00$). As long as the demand-capacity ratio of the runway is not substantially altered, the required delay absorption remains similar. When increasing the take-off time estimate error, however, delay absorption increases, resulting in a significant difference between U/120 and U/0 ($z = 2.67, p = 0.008$). This can be attributed to the fact that with pre-planning errors, more aircraft need to absorb larger delays, are informed about this at a late stage and therefore require inefficient delay absorption at low altitude. Compared to the baseline, however, none of the degraded estimate conditions show a significant difference.

Delay energy cost is illustrated in Figure 10. A main effect was not observed ($\chi^2(4) = 9.40, p = 0.052$), and post-hoc tests only revealed a significant difference between conditions U/0 and U/120 ($z = 2.98, p = 0.003$). Once take-off time estimate accuracies deteriorate, cost increases. For the conditions in which estimate errors were included in the pre-planning scheduler, no statistically significant differences were identified when compared to the baseline condition. Figure 10, however, does illustrate a tendency of growing energy cost when inaccuracies are included in the pre-planning scheduler.

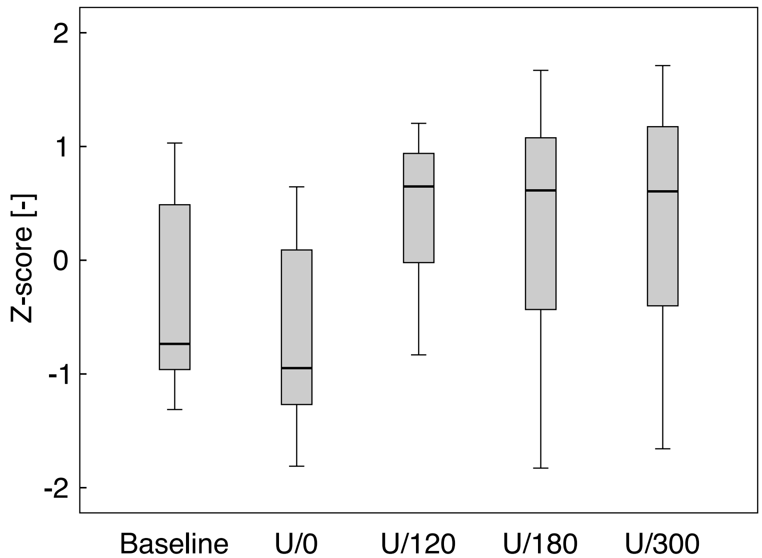

Figure 10. Delay energy cost.

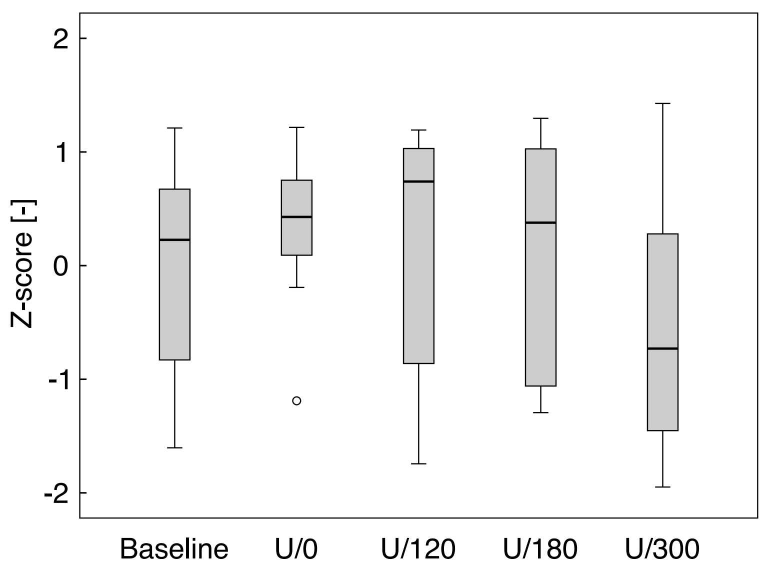

Figure 11. Average runway inter-arrival time.

2. *Runway Capacity*

Figure 11 shows the runway capacity in terms of inter-arrival time for the landing runways. A main effects test revealed no significant effect of pre-planning on the runway inter-arrival time ($\chi^2(4) = 4.98, p = 0.29$). Tentatively it can be concluded that as long as the demand evolution remains similar, runway capacity is not affected.

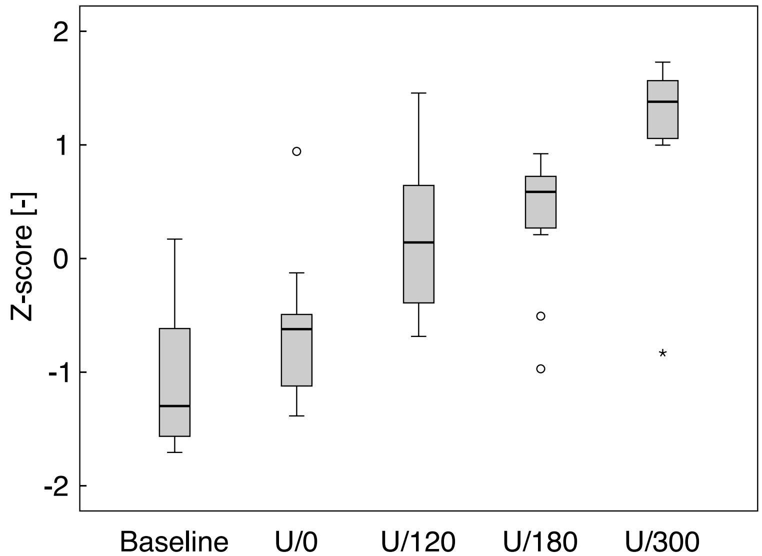

Figure 12. Arrival sequence position changes.

3. *Sequence Stability*

Figure 12 shows the sequence stability results in terms of the number of position changes. A main effects test revealed a significant influence of pre-planning on the number of position changes ($\chi^2(4) = 32.82, p < 0.001$). Post-hoc tests revealed no significant effect of pre-planning with accurate estimates (U/0), compared to the baseline ($z = 1.57, p = 0.12$), although there is a tendency of increased position changes in U/0. This is remarkable, as one would expect the opposite. Additional analyses showed that the increase of position changes is due to the re-scheduling that takes place, even when the pop-up flight departs exactly at its estimated take-off time. The schedule revision has a minimal disturbing effect with perfect pre-planning, but it turned out that flights far away from the TMA (often still outside of the freeze horizon, but with a fixed STA[e]) are subject to re-planning and therefore trigger position changes to occur around the AMAN horizon. Compared to the baseline, the number of position changes increases significantly for all of the deteriorated estimate conditions ($0.002 < p < 0.006$). Analysis showed that, in these cases, the majority of position changes is due to the inaccurate take-off time estimates of pop-up flights. Average statistics of deteriorated condition U/300, for instance, show an increase of 79% in the number of position changes, when compared to the baseline. Once airborne, pop-up flights need to be re-scheduled, thereby also impacting other aircraft. The results therefore indicate that, even when the take-off time accuracy is two minutes, it is better to not pre-plan pop-up flights. This effect worsened for larger take-off time inaccuracies.

4. *Flight Crew and ATC Task Load*

The results in terms of STA revisions are shown in Figure 13. The main effects test revealed a significant effect of pre-planning on STA revisions ($\chi^2(4) = 41.24, p < 0.001$). Post-hoc tests revealed a significant improvement between the perfect pre-planning condition (U/0) and the baseline ($z = 3.06, p = 0.002$), with an average improvement of 38%.

Significant differences were also found between the perfect pre-planning condition and deteriorated condition U/120 ($z = 3.06, p = 0.002$), as well as between the baseline condition and the deteriorated precision

[e]Sometimes aircraft receive their STA already while still outside the AMAN freeze horizon, because of specific phenomena (e.g. aircraft overtaking effects, asymmetrical structure of airspace, etc) occurring around the AMAN horizon.

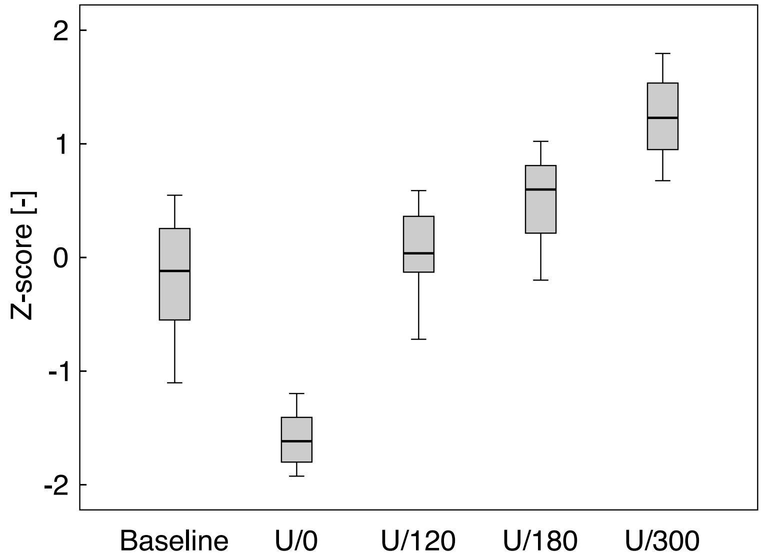

Figure 13. STA revisions.

conditions for condition U/300 ($z = 3.06, p = 0.002$). In each of these cases, performance worsened with increasing planning uncertainty.

Because with the pre-planning scheduler, pop-up flights have a reserved place in the sequence, schedule revisions are largely unnecessary when flights depart at the estimated time. When take-off time estimate errors are introduced, however, the number of required STA revisions and the number of affected aircraft increase. In this case, pop-up aircraft are pre-planned using the wrong take-off time estimates. Once airborne, they will have to be re-scheduled, possibly also impacting other airborne aircraft. The larger the estimate errors, the more revisions and impacted aircraft, as can be seen in Figure 13.

Figure 14 shows the number of disturbed descents. Here, a main effects test revealed a significant impact of pre-planning on the number of disturbed descents ($\chi^2(4) = 31.96, p < 0.001$). Post-hoc tests, however, only revealed significant differences between the baseline and U/300 conditions ($z = 2.95, p = 0.003$). Nevertheless, it can be seen in Figure 14 that when the take-off time estimate errors increase, there is a tendency towards a growing number of disturbed descents. The actual effect is small because most pop-up aircraft depart further away from the airport than the Top of Descent (ToD) of airborne flights.

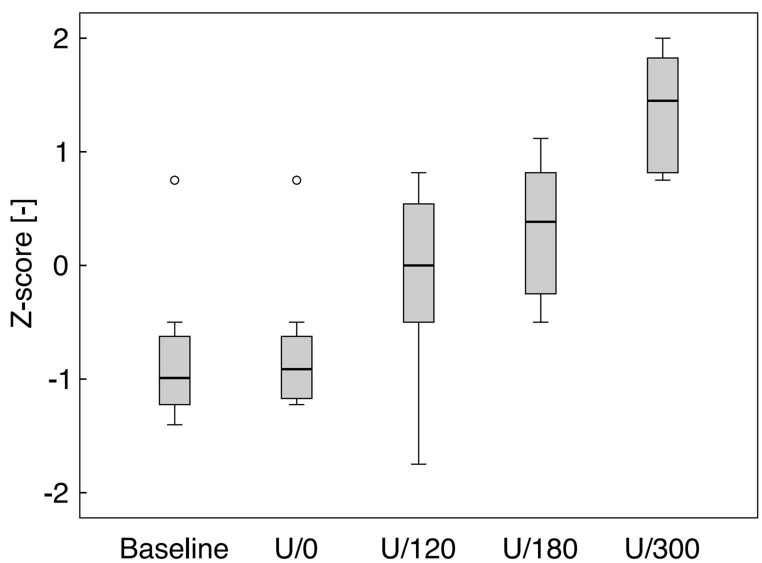

Figure 14. Disturbed descents.

VI. Discussion

The simulations in this paper focused on assessing the effect of pop-up flights on the (extended) arrival management process. In addition, it was analysed whether this negative impact could be mitigated by pre-planning pop-up flights prior to departure. Statistical results, both from the main and post-hoc tests, are summarized in Table 7 for both studies.

Table 7. Summary of Statistical Results

	Study I			Study II					
	Main test	Post-hoc tests		Main test	Post-hoc tests				
		E/0-E/100	E/100-E/200		B-U/0	U/0-U/120	B-U/120	B-U/180	B-U/300
Average low-altitude delay abs.	○			∗	○	∗	○	○	○
Delay energy cost	∗	○	∗	∗	○	∗	○	○	○
Runway inter-arrival time	○			○					
Position changes	∗	∗	∗	∗	○	∗	∗	∗	∗
STA revisions	∗	∗	∗	∗	∗	∗	○	○	∗
Disturbed descents	∗	○	○	∗	○	○	○	○	∗

∗ significant ○ not significant

A. Effect of Pop-Up Flights

For E-AMAN, several trends and tendencies can be observed. First, when the number of pop-up flights increases, there is a large negative and significant effect on flight crew and ATC task load, as well as on sequence stability. This is revealed by the increased number of STA revisions and position changes. When pop-up occurrence increases, the number of disturbed descents does too, although this is not a statistically significant result. Moreover, the magnitude of the corresponding effect is negligible. The average low-altitude delay absorption is not significantly affected by pop-up scaling. The same observation was made for the runway inter-arrival times, implying that runway capacity is not significantly affected by pop-up occurrence. Delay energy cost grows when pop-up occurrence increases. In case the pop-up occurrence was doubled, this cost increase would be significant and largely negative. As hypothesized, the occurrence of pop-up flights has a significant and large negative effect on delay (cost) (hypothesis 1-1) and sequence stability (hypothesis 1-3), as well as on flight crew and ATC task load (hypothesis 1-4). These effects and tendencies are clear when observing current levels of pop-up occurrence within the context of E-AMAN. In addition, these issues grow when the pop-up occurrence is doubled, clearly illustrating that pop-up flights negatively affect the extended arrival management process. As runway capacity is not impacted, hypothesis 1-2 (runway capacity reduces with increasing number of pop-up flights) cannot be supported.

Most of these effects are observed in the context of AMAN as well. However, due to the lower number of pop-up flights, the impact is smaller when compared to E-AMAN, and is therefore often not statistically significant. This finding confirms hypothesis 1-5 (effects of pop-up flights are larger for E-AMAN).

B. Horizon Extension

It was also assessed whether a horizon extension, from the AMAN to E-AMAN context, is beneficial in terms of overall system performance. On the one hand, this extension positively affects the delay (cost): the required low-altitude delay absorption is reduced by 17%. Also the delay energy cost reduced by 22% on average. The number of disturbed descents was reduced to nearly zero, although their occurrence (9%) in AMAN is not considered problematic either. Runway capacity is not significantly affected by the horizon extension. On the other hand, the number of STA revisions increases by a factor 27 when extending the horizon. In addition, the number of position changes is negatively impacted, on average by a factor 6. Obviously these negative effects are induced by the large increase of pop-up flights in the E-AMAN context. In the current AMAN situation, there are almost no pop-up flights, which implies that their negative impact is small. The research therefore illustrates that a solution needs to be found when extending the AMAN horizon. As hypothesized, the horizon extension has a clear benefit in terms of reduced delay (cost) (hypothesis 1-6). On the other hand, sequence instability grows, confirming hypothesis 1-8, and flight crew and ATC task load increase (confirming hypothesis 1-9). Because runway capacity is not impacted, hypothesis 1-7 (runway capacity reduces when extending the AMAN horizon and absorbing more delays upstream) can not be supported.

C. Alternative Scheduler

The advantages of an AMAN horizon extension are large, and therefore should be pursued. However, mitigation actions need to be taken to limit the observed negative effects of increased pop-up occurrence. It was analysed whether pre-planning pop-up flights prior to departure, using their take-off time estimates, is beneficial. An alternative scheduler was developed that explicitly schedules and pre-plans pop-up flights prior to departure. By comparing this alternative pre-planning scheduler with the baseline scheduler, it could be assessed whether pre-planning pop-up flights is beneficial. It was observed that pre-planning is beneficial, but only when there are no take-off time estimate inaccuracies. In this case, the number of STA revisions could be reduced by 38%. This is positive in terms of flight crew and ATC task load. In addition, both schedulers result in similar performance in terms of average low-altitude delay absorption, the number of position changes, disturbed descents and the delay energy cost. Moreover, there is no significant effect on runway capacity. Pre-planning is therefore mainly beneficial in improving task load, and thereby outperforms the baseline scheduler, as hypothesized (hypothesis 2-1). It is however important to realize that it relies on perfectly accurate and reliable take-off time estimates. In reality, however, flights are often delayed prior to departure - in the order of minutes - for various reasons, and therefore this requirement seems unrealistic.

If the take-off time estimate error increases to 120 seconds, the conclusions change. In terms of the number of STA revisions, the alternative scheduler no longer outperforms the baseline scheduler. In addition, the scheduler performs statistically significantly worse in terms of position changes (+50%). Moreover, there is a tendency - although not statistically significant - which indicates an increase in the average required low-altitude delay absorption (+5%) and the delay energy cost (+2%). Even when estimate accuracies of 2 minutes would be achievable, the results show that it is better to discard the information and not pre-plan pop-up flights prior to take-off. Hypothesis 2-2 (pre-planning pop-up flights is beneficial when take-off time inaccuracies are smaller than three minutes) is therefore not supported by the results. Overall, the alternative scheduler's performance deteriorates with increasing take-off time estimate errors. With an estimate uncertainty of five minutes, the scheduler is outperformed by the baseline scheduler in all observed metrics.

These findings are similar to the outcomes of a NASA study [12] on the *Multi-Center Traffic Management Advisor*, the United Sates equivalent of E-AMAN [19]. In this study, it was examined whether it is beneficial to pre-plan pop-up flights prior to departure. During the study, it was concluded that it is better to discard the inaccurate take-off time estimates for pre-planning purposes. Rather, it is better to schedule the pop-up aircraft only once airborne. These conclusions are consistent with the findings in this research project: discard inaccurate estimates in the context of arrival management, as they disturb the process more than they improve it. Accurate estimates are required and can result in overall benefits for AMAN and E-AMAN. However this is only the case when the take-off time estimate errors are actually eliminated. Similar conclusions were found for a study [18] that assessed whether take-off times could be tuned in order to avoid en-route conflicts. As in the context of arrival management, the required accuracies are highly demanding. It was observed that the (positive) effect diluted as the pre-departure estimate uncertainties were increased [18]. Similar to the context of arrival management, very accurate information is required for pre-planning aircraft prior to departure. If this is not the case, it is better to discard the information and not pre-plan pop-up flights.

The Collaborative Decision Making (CDM) and Advanced ATC Tower concepts have proven their value, as take-off time estimates are becoming more reliable and accurate. In the context of Air Traffic Flow & Capacity Management (ATFCM), these improved estimates are crucial for improving predictions on ATC sector counts. Due to the nature of the arrival management process, the required accuracies are substantially higher when compared to ATFCM. The current estimated take-off time window is still in the order of minutes, which implies that the information is insufficiently accurate for using it effectively in AMAN and E-AMAN. When considering that currently take-off time estimate accuracies in the order of five minutes are achievable, it has been shown that it is better to discard the estimates and not pre-plan pop-up flights prior to departure.

VII. Conclusion

To assess the effect of pop-up flights on arrival management, simulations were performed using an AMAN research model. The effect of pop-up flights, both in the context of arrival management (AMAN) and extended AMAN (E-AMAN), has been analysed for Amsterdam Schiphol Airport. In addition, it was assessed whether it is beneficial to pre-plan pop-up flights, prior to departure, using their take-off time estimates.

Results show that pop-up flights negatively affect the (extended) arrival management process, in terms of flight crew and air traffic control task load, sequence stability and delay (cost). When extending the AMAN horizon, the occurrence and effect of pop-up flights grows substantially, such that mitigation actions are needed. Pre-planning pop-up flights is beneficial, mainly in terms of flight crew and ATC task load, but only if the pre-departure take-off time estimates (for pop-up flights) are highly accurate. If the accuracy deteriorates to 2 minutes or more, it is not considered better to pre-plan pop-up flights. When pre-planning using currently achievable estimate accuracies of approximately 5 minutes, it was observed to result in worse overall performance when compared to the situation in which pop-up flights are only considered once airborne. The more deteriorated the estimate accuracies, the larger the negative effects of pre-planning pop-up flights. More research on the topic is required to identify an achievable manner for dealing with pop-up flights efficiently. Follow-on research should also focus on other airports, and off-peak periods.

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