Operational measures to reduce environmental impact of arrivals using fixed routes and higher initial approaches

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***Abstract*— Since the Paris Climate agreement and the European Green Deal that aims to make Europe climate neutral by 2050, the environmental impact of aviation is scrutinized strongly by the wider public and the government, at least in the Netherlands. This is mainly related to noise hindrance and NOx emissions (and NOx deposition), but also CO_2-emissions. To reduce this impact, a vast number of measures are implemented or considered. In general three categories apply: (a) reduce the number of traffic movements at an airport, (b) fleet renewal - replace older aircraft by newer ones, and (c) operational measures.**

The operational measures studied in the Single European Sky ATM Research (SESAR) project 'Integrated TMA, Airport and Runway Operations (ITARO)' focusses on future operations and traffic handling by Air Traffic Control (ATC) within the Terminal Manoeuvring Area (TMA). The timeframe considered is around 2035.

This paper describes the results of human-in-the-loop Real-Time Simulations (RTSs) carried out for project ITARO using NLR's ATC Research Simulation (NARSIM) facility, where a new operational method has been implemented and evaluated within the Schiphol TMA environment. The new operational method is an integration of a number of operational improvements, including several SESAR Solutions, to support knowledge development on a potential new operational concept foreseen by the Dutch Airspace Redesign Programme (DARP):

- **Fixed arrival and approach routes designed based on Required Navigation Performance (RNP) specifications, e.g., RNP-AR (Authorization Required) to enable Established on RNP (EoR) operations in support of independent parallel approaches;**
- **Fixed angle initial approach segments out of FL100;**
- **Schedule delivery at the TMA entry points improved to an accuracy in the order of ±30 seconds;**
- **The controllers are provided with a merge support tool;**
- **Interval Management (IM) operations available to the controller's toolbox to very accurately control the inter-aircraft spacing at the merge point in the TMA and further down to the Final Approach Point; and**
- **Separation minima on the final approach track is based on RECAT-EU Pair-Wise Separation (PWS). The tool to inform the controller about the minimum distance between aircraft pairs also includes compression on final approach, the Minimum Radar Separation (MRS) and Runway Occupancy Times (ROT).**

One of the identified gaps is the radar separation minimum to be applied during the intercept of the final approach track; it transitions from 3 NM in the TMA to 2.5 (or even 2.0) NM on final approach. Another gap is the discrepancy between the time-based IM operations and the distance-based merge support tool. The RTSs also included a number of non-normal events (e.g., go-arounds, less accurate delivery at the TMA entry points for some flights, aircraft being unable to perform RNP and/or IM operations, unfavorable strong winds). A point of attention of the new operational concept is a gross schedule deviation at the TMA entry points, causing (late) sequence changes. The general conclusion was however that the integration of the above-mentioned operational improvements worked quite seamlessly and was straightforward for the controllers to deal with.

Keywords—ATM, TMA, fixed routes, fixed profile descents, IM, ORD, EoR, RNP-AR, RTS, NARSIM, descend via, merge support, aviation emissions, aviation noise.

I. Introduction

Current operations at Amsterdam Airport Schiphol is characterized by the use of Standard Instrument Departures (SIDs) for departing aircraft and radar vectoring from the TMA entry fix to the final approach track for arriving aircraft. To reduce noise hinderance around Dutch airports and to reduce aviation emissions while also making the Dutch airspace future proof, the Dutch Airspace Redesign Programme (DARP) [1] is first of all redesigning the airspace in the Netherlands. Secondly, a new operational concept is developed and deployed. This operational concept is based on three pillars: (a) more predictable traffic flows - predictable where possible and flexible when needed, (b) fixed routes below FL60 to concentrate the traffic flows and consequently the noise impact – this applies to both departures (as is today) and arrivals (new, where the arrivals are currently being vectored during daytime operations), and (c) continuous climbs and descents. This new operational method, as described in the preferred variant of the DARP, is characterized by the use to fixed routes in the TMA also for arriving aircraft combined with continuous descent.

Considering the new operational method, the research performed by Royal NLR, the Netherlands Aerospace Center, in the Single European Sky ATM Research (SESAR) project 'Integrated TMA, Airport and Runway Operations (ITARO)' [2] focused on future operations and traffic handling by Air Traffic Control (ATC) within the Terminal Manoeuvring Area (TMA) to support knowledge development on a potential new operational concept foreseen by DARP. The timeframe considered in the project is around 2035, which is at the end or even slightly beyond the timeframe considered by the DARP.

The main aim of the ITARO project is providing a fast track to improve terminal airspace, airport and runway operations throughout Europe, while enabling greener flights and improved punctuality (e.g. less delays) thereby contributing to Europe's 'Green Deal' [3]. The project focused on the integration of several SESAR solutions, see details on those inside the SESAR European ATM Masterplan [4] and (pre-) deployment items, already validated to high TRL levels individually, but being combined for a first time in an operational environment. All these endeavors foster bridging the gap from Research & Development to (pre-)deployment, optimizing the overall network performance whilst retaining the individual solution benefits, for instance like increasing capacity or greening the environment.

This paper introduces the individual operational improvements that have been integrated into the new operational method. The new operational method is implemented into NLR's ATC Research Simulation (NARSIM) facility to perform human-in-the-loop Real-Time Simulations (RTSs) within the Schiphol TMA environment. The most interesting results and outcomes of the RTSs are described in the paper, as well as next steps, future research and operational implementation needs.

II. New Operational Method

Amsterdam Airport Schiphol is one of the busiest airports in Europe and is located in a highly populated area of the Netherlands. To realize fixed arrival routes in the Schiphol TMA, with very high traffic demands, a number of building blocks need to be developed and subsequently deployed. Besides the route structure, a key element is a more precise delivery at the TMA entry points in accordance with the arrival sequence and schedule. Thereafter, the Approach air traffic controllers will have to manage arriving traffic along the fixed routes and fixed descent profiles while taking care of inbound/outbound conflicts, merging inbound traffic flows and spacing in-trail aircraft towards and on final approach track, given a very high traffic demand. To support these controller tasks, procedures and support tools have been developed within SESAR and have been individually validated. The new operational method assessed by NLR in the ITARO project integrates a number of these procedures and support tools:

- RNP approaches and RNP approach transitions within the Schiphol TMA, from TMA entry points to runway thresholds, in support of the environmental goals of DARP;
- Fixed profile descents out of FL100, in support of the environmental goals of DARP and also to provide predictability and uniform operations to the controllers;
- Descend via procedures, as published by ICAO, to support operations along fixed profile descents [5];
- Established on RNP (EoR) procedures, also as published by ICAO, in support of independent parallel approaches at Schiphol [6];
- Indications of the start of final descent out of FL100, in support of both inbound/outbound conflict management and descend via procedure;
- Indications of the start of RNP-AR Approach procedures at an altitude of FL70, in support of the EoR procedures;
- A distance-based merge tool to support the task of merging two traffic flows on fixed routes as typically two traffic flows merge towards a single landing runway;
- An extended Optimized Runway Delivery (ORD) tool to support the task of precise delivery on final approach [7]. The tool to inform the controller about the separation minima between aircraft pairs also included compression on final approach and is based on the most limiting distance between RECAT-EU Pair-Wise Separation (PWS) [8], involving dedicated wake minima for many aircraft type pairs, the Minimum Radar Separation (MRS) and Runway Occupancy Times (ROT); and
- Interval Management (IM) procedures to support merging of traffic and precise delivery on final approach. IM operations controls very accurately the inter-aircraft spacing at the merge point in the TMA and further down to the Final Approach Point [9][10].

The new operational method integrates RNP based arrival and approach operations with IM operations. In combination with environmentally favourable Continuous Descent Operations (CDOs), this new operational method inherently aims at reducing aviation emissions in high density TMA environments. This RNP/CDO/IM integration is expanded to final approach for Time-Based Separation (TBS) whilst applying a minimum aircraft separation derivation via the ORD tool from RECAT-EU PWS minima, MRS and ROT related separation impact. CDO and IM are generally initiated outside the TMA, CDOs preferably at the top of descent.

III. Simulation Set Up and Exercises

A. *Aims and Objectives*

The ITARO simulations were conducted in two periods in 2022. This paper reports on the second RTS conducted in the fourth quarter of 2022. The RTS focused especially on controller aspects (e.g. Controller Working Position (CWP) Human Machine Interface (HMI), working procedures, workload, acceptance) and ATC tool-integration in order to assess the workability of the new operational methods and to identify gaps and need for further development of procedures and HMI [11].

The main validation objectives of the RTSs were related to human performance and safety. The human performance objectives were addressed through questionnaires (post-run and end-of-day), debriefings (post-run and end-of-day) and observations supported by video and audio recordings. The safety objectives were also partly addressed by the questionnaires, debriefings and observations, but also by analyzing recorded data on separation infringement. It is worth mentioning that for two positions complementary measurements were made with eye-trackers to get more insight in the spread of attention among areas of interest on the radar screen, see also figure 1.

Fig. 1. Calibrating the eye-tracker prior to a run at NARSIM.

B. Simulation Environment

The high fidelity human-in-the-loop RTS platform NARSIM, located at the Royal NLR premises in Amsterdam, was used to perform the simulations. The NARSIM Radar was configured with the airspace, air traffic controller HMI adaptations and the implementation of tools and procedures in accordance to the new operational method. In addition to air traffic controllers, pseudo-pilots interacted with the simulated aircraft.

The NARSIM set-up consists of five CWPs:

- Two executive controller positions (i.e. one Feeder and one Arrival Controller) for the eastern part of the Schiphol TMA, TMA-East;
- Two executive controller positions (i.e. one Feeder and one Arrival Controller) for the western part of the Schiphol TMA, TMA-West; and
- One Approach Planner position.

Figure 2 provides a schematic overview of the areas of responsibility of the controllers. Note that the Feeder controllers also control the departures and one of their main tasks is detect and resolved inbound/outbound conflicts.

The schedule delivery at the TMA entry points is improved to an accuracy in the order of ±30 seconds. The route structure of both arrivals and departure in the RTSs is shown in Figure 3. From the TMA entry points, for example RIVER in the south-west, RNP approach transitions are defined up to the start of the RNP-AR procedures. These procedures start at the IAFs and end at the runway threshold. Specific features are included in the two RNP-AR approach

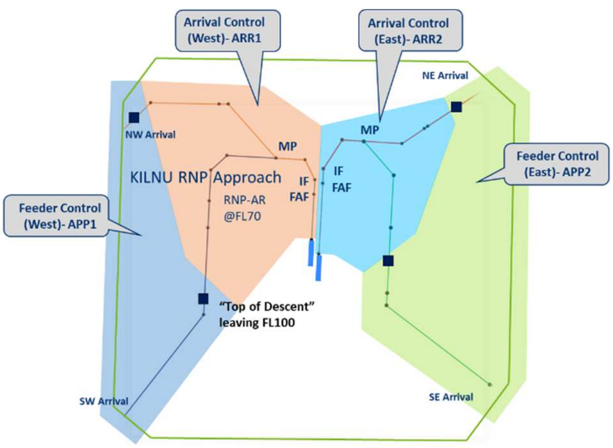

Fig. 2. Areas of responsibilty of Approach controllers.

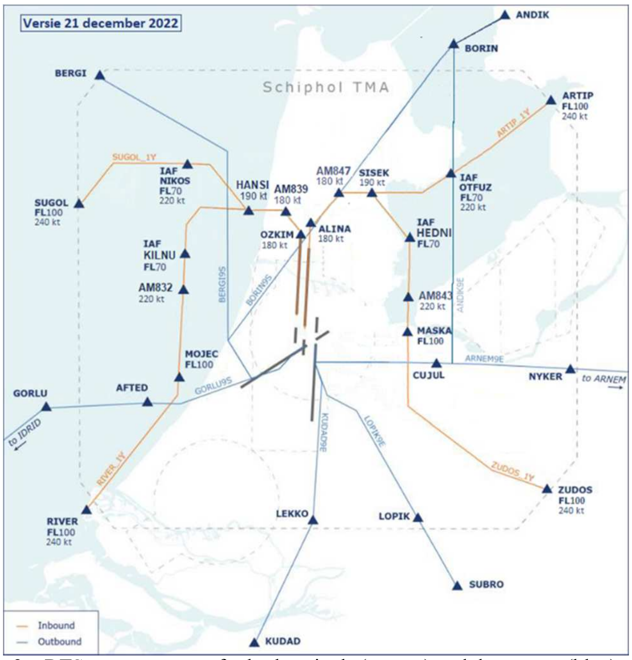

Fig. 3. RTS route structure for both arrivals (orange) and departures (blue).

procedures to support the independent parallel approach operations through the EoR procedure. The fixed profile descent is made up of two segments:

1. Fixed descent angle in the range of 2.0-2.4 degrees to accommodate strategically separated inbound/outbound crossings within the Schiphol TMA, starting at FL100, for example at MOJEC for traffic arriving via the south-western corner. Typically, an outbound flight could climb to FL90 whereas the inbound flight is flying at FL100 and its fixed angle descent would only start after passing the crossing point; and
2. 3-degree final approach path starting at the Final Approach Fix (FAF).

C. CWP Indicators and Tools

The controller is supported by additional indications and tools as compared to current operations. A snapshot of the radar display is presented in Figure 4. The indications show the following:

- The location of the start of final descent out of FL100 through a grey solid circle;
- The location of the start of the RNP-AR approach procedure through the presentation of the initial waypoint of that procedure, which also gives the name of the procedure, e.g. KILNU waypoint for the KILNU RNP Approach; and
- The location of the merge point through the presentation of the waypoint, for example HANSI. It should be noted that the merge point is also part of the second and final part of the IM clearance (e.g. "Cross HANSI at 84 seconds").

In addition, three new tools were available for the controller: the Extended ORD tool, the merge support tool and IM operation.

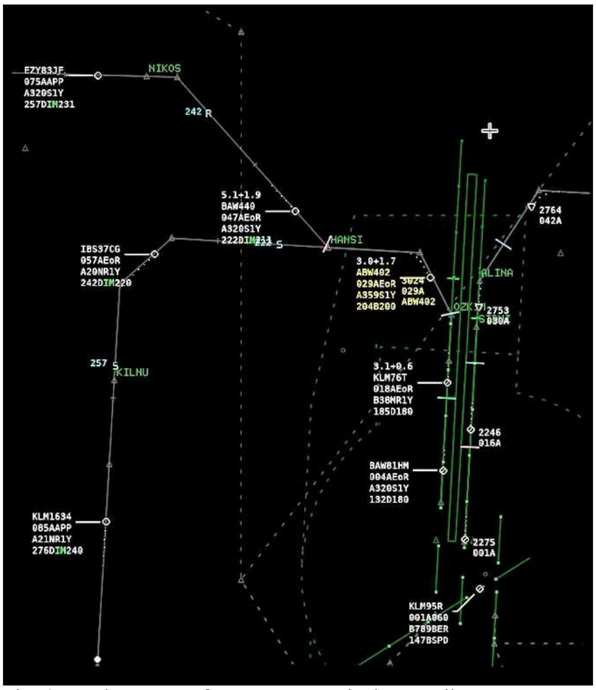

Fig. 4. Radar screen of TMA-West Arrival Controller.

Firstly, the extended ORD. The ORD is presented to the controller through short lines on the route from the merge point onwards, the so-called Target Distance Indicators (TDI). These are time-based markers indication the position a trailing aircraft should be behind a leading aircraft in order to comply with all applicable separation minima and expected ROT of the lead aircraft. This marker includes the compression effect of aircraft slowing down in steps towards their final approach speed. For maximum throughput the aircraft should be on its marker, for safety it should be on or behind its markers (in general on short final).

Secondly, the merge support. The merge support is presented to the controller through a distance-based ghost symbol of an aircraft. The distance from the current position of an aircraft, while flying prior to the merge point on route A, to the merge point is calculated along the route A. This distance is than used to determine a ghost position on the other route, say route B, towards the merge point. The ghost is presented in cyan with a letter, e.g. an R for an aircraft arriving via RIVER, together with the current groundspeed of the aircraft.

Thirdly, the IM operations. For IM operations the approach controller tasks the flight crew to merge behind a lead aircraft with a specified time interval and then maintain that interval until the FAF, the IM planned cancellation point. For example, KLM123 on the RIVER transition is to achieve an interval of 82 seconds at the merge point (also known as IM cross point) behind TRA456 on either RIVER or SUGOL transition, and then to maintain that interval until the FAF. The IM clearance could be "KLM123, CROSS HANSI AT 82 SECONDS". It should be noted that the IM clearance needs more information, but in this simulation set-up that information is already given to the aircraft prior the entering the Schiphol TMA. It includes the target aircraft identification and its intended flight path information, e.g. "Target aircraft is TRA456 on the SUGOL 1Y TRANSITION, NIKOS RNP APPROACH", and the planned cancellation point being the FAF of the KILNU RNP approach runway 18R. Upon transmitting (via voice communications) the IM clearance, the approach controller also enters the clearance on its CWP. Most prominently, the radar label of the aircraft now shows that IM is active based on this entry and a confirmation from the aircraft that IM is active through Mode S datalink register 71, the Interval Management report. The fourth line of the radar label shows "IM" in green followed by the current indicated airspeed. The so-called on request window also presents detailed IM information of a controller selected aircraft, the one with the yellow radar label. Figure 5 gives an impression of the CWP set-up at NARSIM.

D. Simulation Activities and Operational Scenarios

The RTS consisted of ten runs of approximately an hour each. In order to compare different scenarios, the following reference and solution scenarios have been defined. Note that the operational method is the reference run which is not similar to current day operations.

- Reference: Fixed route structure with fixed profile descents with the merge tool and a basic ORD tool.
- Solution: Fixed route structure with fixed profile descents with all tools including IM and an enhanced ORD tool.

Each run had the identical traffic sample (with variation in callsigns) to be able to compare the results. Thus the traffic demand was not varied, at a very high level of 40 landings per hour per runway in order to generate stressing conditions. In addition, the following variations have been applied to the runs:

- Wind: Calm wind conditions (5 kts) and strong wind conditions (50 kts from the south at 10,000 ft, reducing to 20 kts from the south on short final);
- IM equipage level: runs have been performed with traffic samples in which 0%, 20%, 80% or 100% of the total arrivals were IM equipped;
- Runs with events: This involved multiple go-arounds, unable RNP, bad delivery of a few aircraft at the TMA entry points well outside the margin of ±30 seconds.


Fig. 5. NARSIM controller working positions.

IV. RESULTS

A. Main Results

The SESAR solutions integrated in this RTS worked well together. In general the air traffic controllers found the integrated operating concept acceptable. Combining these solutions did not reveal any negative effect on runway throughput. No major human performance, safety or environmental issues or concerns have been identified.

Environmental benefits were achieved through the very high level of adherence to flying fixed routes and continuous descent and climb paths enabled by the integrated concept in high traffic demand conditions.

Reference [11] provides detailed information and results, the next sections show the main results related to human performance, integration of the various new technologies and IM.

B. Human Performance Results

ATCO workload was measured with the NASA-TLX rating scale. The average NASA-TLX ratings were between 20 and 45, see figure 6. These values should be considered with care as the number of subjects, hence ratings, for each run was low, but in combination with the debriefing feedback it gave a good indication that workload is not an issue. The ratings of the run with 100% IM equipage were higher compared to all other runs, contrary to what was expected. This is most likely due to unintended and more importantly unnotified sequence changes (a simulation problem) encountered during this run. For the run with more variation in schedule delivery and the run with go-arounds, the workload rating was higher as expected, but only slightly. For the other runs no increases in average ratings were found, while the sustainable arrival runway throughput was 40 landings/hour per runway for each run.

The acceptability of the concept was assessed with a post-run questionnaire, the results are presented in figure 7. Again care should be taken as the number of subjects for each run was low. ATCOs mentioned that they felt confident provided that speeds of flights reduce gradually towards the final approach track (an item identified for further refinement), that traffic is delivered accurately at the TMA entry points (within ±30 seconds of the scheduled time). As stated during the debriefings and also obvious from this figure, a scenario in which only 20% of the aircraft are equipped with IM is not desirable and not wanted, as operational benefits are deemed absent with so few aircraft equipped.

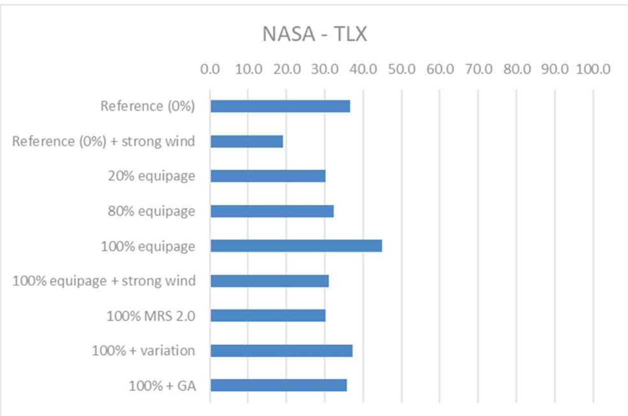

Fig. 6. NASA Task Load Index (TLX) ratings for varied IM equipage percentages.

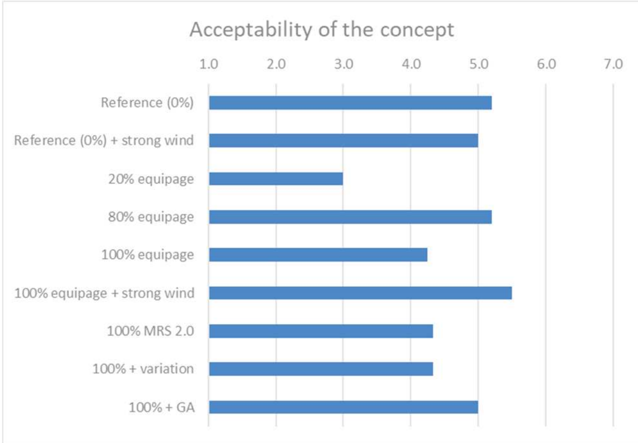

Fig. 7. Acceptability questionnaire results for varied IM equipage percentages.

The concept did lead to a concern, expressed by air traffic controllers, about a potential attention shift away from monitoring the traffic that is turning in for final approach and being able to instruct interventions when necessary. This concern is related to independent parallel approach operations. Further research is needed to determine whether the concern is an actual issue.

C. Integration of New Technologies

General findings are considered the most important results of the RTS as they represent the aspects related to the integration of the SESAR solutions. The integration did not reveal major issues, but a few topics could benefit from further refinements.

- The Target Distance Indicator (TDI) display and calculations have to be along the published fixed approach route instead of along the extended runway centreline. It has to consider turns, winds and speed profiles along the route. This finding was validated.
- The transition from the MRS of 3 NM as currently applicable in the TMA to an MRS of 2.5 NM (or 2.0 NM) on the final approach track needs further attention. Several methods can be envisioned to design this transition.
    - The presentation of the TDI would gradually reduce the separation to the applicable separation distance, while also taking into account the compression effect on final.
    - Though when the 3 NM separation distance is the most stringent, the TDI on short final may still indicate a value slightly above 2.5NM (or 2.0NM).
    - However one could also think of a more abrupt change in TDI presentation once both aircraft are established on the extended centreline.
- The IM Achieve-by Point, that is the ATCO assigned point at which the IM spacing goal needs to be achieved, not only needs to support the ATCO task to space aircraft very precisely on the final approach track to retain/increase runway capacity, but also needs to support the ATCO merge task earlier on.

The Achieve-by Point therefore needs to be located not later than the merge point of the fixed approach routes. This finding was validated.

- IM spacing goal determination, based on integration with Arrival Manager (AMAN) and ORD tools, could be further improved. The spacing goal was based on the minimum separation between aircraft pairs (obtained from the ORD tool) as well as arrival planning information (from AMAN) to not only increase runway capacity by setting the spacing goals to the minimum separation, but also considering operations in accordance with the planning. However, this resulted in front-loading behavior. Front-loading is either applying route shortcuts or, as in this case, speeds above standard speeds in order to create more space for subsequent traffic, it is a method applied to better cope with high demand of traffic. The front-loading behavior in the RTS was a direct result of the choices made in the IM spacing goal determination, it resulted in airspeeds beyond the merge point (the IM Achieve-by Point) and in particular on the final approach track that were found to be too high.

- The combination of the fixed route presentation with the distance-based merge tool and IM operations has been positively received by the Approach controllers participating in the RTS. However, it was suggested to explore whether the IM Clearance could be given by Area Control (ACC) as the arrival sequence is already known before entering the terminal airspace. This gives more time to correct errors and could further reduce the communication task load of the Approach controllers. Furthermore it was questioned whether in real life the merge tool should already be presented so early. The ghost blip was already presented on the long approach transitions when the aircraft was still under control of ACC and also for a significant amount of time, hence potentially not stable on a route to the TMA entry point.

- The integrated solutions could handle high traffic loads very efficiently for nominal operations and single aircraft events/disturbances. However, the use of fixed routes with a very high traffic load, and therefore high pressure on the ATM system, will need additional measures (e.g., tools or working methods) to create room in the arrival planning to cope with challenging (e.g., multi aircraft) events/disturbances. A level of flexibility is needed.

D. IM Results

The IM benefits are not directly obvious when observing the controllers and also the rating scales and the questionnaire results didn't indicate clear human performance benefits or human performance costs of IM. Therefore, a more detailed analysis has been performed on the delivery accuracy at the FAF, the planned cancellation point of the IM operations.

Figure 8 shows the actual distance between the current aircraft position and the marker of the ORD tool when the aircraft passes the FAF, as a function of the sequence of landed aircraft. The blue line present the scenario in which the ATCO issues speed instructions to merge and space the

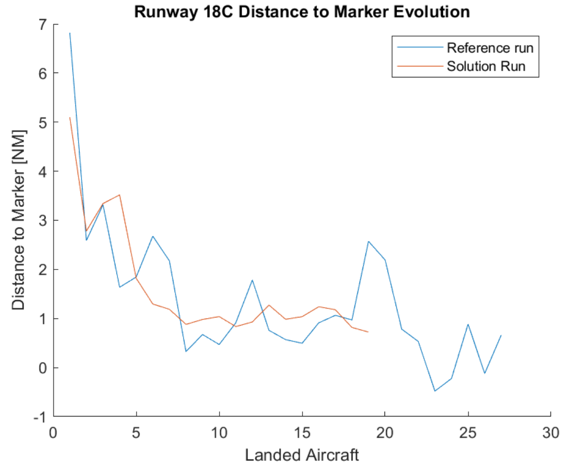

Fig. 8. Evolution of spacing margin at the FAF on runway 18C in one simulation run.

aircraft, the orange line present the scenario in which all aircraft with the use of IM achieve a controller defined spacing interval at the merge point and subsequently maintain that interval until the FAF. The initial part of the curves, the first five to six aircraft, shows a strong decrease of the margin to the ORD marker. This is due to the start of the traffic scenario in which the amount of traffic is gradually built up. Thereafter, the sustained traffic demand is at a very high level. The main result for IM is a very stable margin of approximately 1 NM, whereas without IM the margin strongly fluctuates between plus 2.5 and minus 0.5 NM. This indicates that the delivery onto final approach is much more consistent with IM, and consequently with IM the traffic demand could in theory be safely increased. For example, a 0.5 NM margin reduction would result in an average landing interval of 80 seconds instead of current 90 seconds, theoretically increasing the sustainable peak-hour capacity from 40 to 45 landings/hour per runway.

The same spacing margin metric is also presented in a box and whisker plot, see figures 9 and 10. These figures clearly shows that although the median sometimes only slightly increases with IM, the dispersion or spread is always much smaller, indicating a more precise delivery at the FAF and ample opportunities to further increase peak-hour capacity.

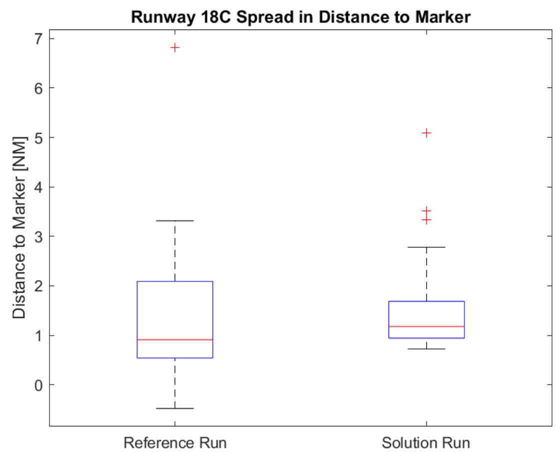

Fig. 9. Spacing margin at the FAF on runway 18C in one simulation run.

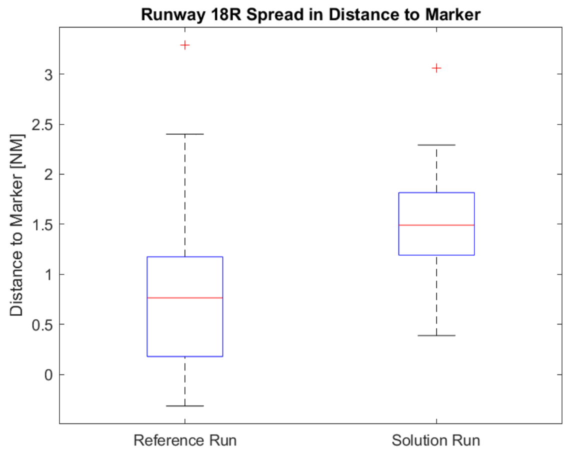

Fig. 10. Spacing margin at the FAF on runway 18R in one simulation run.

V. Conclusions and Recommendations/Next Steps

It was demonstrated that combining the SESAR solutions under investigation does not have a negative impact, that is no gaps were identified on airspace capacity, runway throughput, predictability, CO2 emissions and noise profiles.

A. Main Conclusions

From a Human Performance perspective, the real-time simulations revealed that the novel integrated operating concept is acceptable to the approach controllers when the accuracy of delivery into the TMA is sufficiently accurate (within ±30 seconds) and IM equipage levels are substantial (e.g., 80%). The air traffic controllers were successful in achieving their tasks.

B. Main Recommendations/Next Steps

It has been demonstrated that combining these SESAR solutions does work. Fixed Approach Routes in combination with Continuous Descent Operations contribute to greening flight operations. The assessed controller tools and working methods are promising to industrialize and deploy. In general, the TMA scope is sufficiently validated, though a number of refinements of the integrated concept have been identified.

It is recommended to expand the scope with Area Controllers to address the delivery of a stable sequence, such that Approach controllers don't have to sequence any more, and on top of that the delivery of the traffic at the TMA entry points with a much higher than today's schedule accuracy. A needed accuracy in the order of max 30-45 seconds, compared to max 2 minutes today. Obviously, the identified refinements should be considered and tested whenever they result in major design changes.

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