Design Principles for a Separation Support Tool Allowing Optimized Runway Delivery

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The research in the wake vortex domain made possible in the last years to tackle airport capacity issues by designing new concepts for wake separations between aircraft on approach and departure. Those new solutions allow for dynamic wake separation reduction depending on aircraft characteristics and weather conditions. Amongst those concepts are found Time-Based Separation (TBS), RECAT Pairwise (RECAT-PWS) and Weather Dependent Separation (WDS). However, the application of dynamic separations entails the use of a spacing delivery support tool. This tool shall compute the applicable time- or distance-based separation minima and provide distance indicators supporting their correct delivery by the controller. Distance indicators have hence to account for aircraft separation compression effects but also for the uncertainties related to aircraft speed and wind evolution. This paper presents the principles used for the design of a demonstrator of such a separation delivery support platform called LORD. The LORD tool makes use of a methodology to mitigate separation infringement and to prevent aircraft under spacing by using an additional buffer on the spacing computation. The use of such buffers allows the separations to be correctly delivered up to a certain 'failure rate' equivalent to what is currently observed at airports while still providing capacity benefits with a better spacing management by the controller in different separation modes (e.g. distance based or time based). To prevent spacing infringement, different support warnings are also implemented in the tool. These warnings are to be used as safety nets to quickly identify potential issues in the approach/landing phase and allow the controller to take corrective actions. The LORD tool was successfully tested by Air Traffic Controllers during Real-Time Simulation campaigns. The use of the new separation concepts together with the LORD tool is seen to allow for an increase of throughput and reduction of separation infringement, while maintaining workload and situation awareness at an acceptable level.

I. Introduction

The demand is high for increasing airport capacity and efficiency at some European airports, in particular for increasing runway throughput from an air traffic management perspective. In 2017 the total IFR movements for European flights (ECAC – European Civil Aviation Conference area) were 4.0% higher than 2016 traffic levels, surpassing the 2008 record-high levels [1]. A continuous growth of this type in the air traffic will lead to a capacity crunch in the next future with European airports not in position to meet the demand. Runway capacity and efficiency is often directly linked to the minimum longitudinal separation between traffic on final approach or between departure traffic. These separation minima are based on surveillance capabilities and on wake turbulence. A solution to airport congestion is thus to reduce, where and when possible, separation minima whilst at least maintaining the current safety level.

Current applicable ICAO PANS-ATM wake turbulence distance-based separation minima for approach and departure were established in the seventies. Since then, aircraft wake vortex phenomenon has been at the core of

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many studies, also in the framework of multiple large scale research projects (see e.g., [2, 3]). Wake measurement data collection campaigns (see e.g., [4]) and extensive simulation studies provided an improved understanding and characterization of wake vortex evolution depending on the generating aircraft and the ambient conditions. Wake encounter flight tests and simulation also allowed a better characterization of the aircraft reaction to wake encounter (see e.g., [5, 6]).

This improved knowledge made possible the design of new wake separation concepts, with some of them already deployed in Europe and US. Time-Based Separations (TBS) and RECAT Pairwise (RECAT-PWS) are part of these new solutions. Those concepts take into account aircraft detailed characteristics and/or wind conditions. Weather Dependent Separation (WDS) concepts, allowing further reduction of wake separation minima under specific wind conditions, are also under development.

The application of such dynamic separations shall also account for parameters that change over time, like the headwind component or the heading and speed of aircraft, instructed tactically by the controller for managing the landing sequence. The application of such dynamic pairwise separation minima therefore entails the use by the controllers of a separation delivery support tool. This tool shall provide controllers with the applicable separation minima but also support them in the separation compression management, which is more challenging when dealing with dynamic separation minima. EUROCONTROL developed a demonstrator of such a tool, called "Leading Optimized Runway Delivery" (LORD). This was performed in the framework of Single European Sky ATM Research (SESAR) Programme, in Project 06.08.01 and currently refined in the SESAR 2020 Programme, in Project 02. A similar tool has been developed in the US, see [7].

This paper presents the design principles of the LORD separation delivery support tool. It details how separation spacing indicators are computed, when associated either to distance- or time-based separations, also taking into account uncertainties on aircraft performance and wind evolution. In order to be approved by safety regulators, there is indeed a need for guaranteeing that the tool computes the correct separations in fault free and faulted conditions. The paper also illustrates how separation delivery support is provided through the associated Human Machine Interface (HMI). Finally, it provides details on some support warnings implemented in the tool and a summary of the results obtained in several real-time simulation campaigns during which the tool was tested.

This paper is organized as follows. Section II details the wake separation concepts that are used in the separation delivery tool. Section III describes the methodology used for computing appropriate separation/spacing indicators in the tool. Section IV presents the HMI of the separation delivery tool, the support warnings and the results of the real-time simulation campaigns. Finally, Section V draws some conclusions and presents the next steps for the future developments of the tool.

II.   NEW WAKE SEPARATION CONCEPTS

The research in the wake vortex domain (see e.g., [4, 5]) made possible in the last years to tackle airport capacity issues by designing new concepts for wake separations between aircraft on approach and departure and improve runway throughput at those constrained airports. These concepts can be divided in two classes: Distance-Based Separation (DBS) concepts and TBS concepts. Finally, the distance- and time- based separation minima can be defined independently of the weather condition or as a function of the wind conditions, such as what is developed in the WDS concepts.

A. Distance-Based Separation concepts: RECAT and RECAT-PWS

The first class of concepts consists in refinements of current distance-based ICAO separation scheme.

RECAT is a joint EUROCONTROL – FAA initiative aiming to renew and optimize the out-of-date currently applied ICAO regulations on DBS (see [8, 9, 10]). Nowadays, the first phase of regional RECAT projects, which consists in defining new distance separation matrices composed of six/seven static aircraft categories instead of three, entered the operational phase and is deployed in several airports in the United States [11] and in Europe (then denoted RECAT-EU) [12, 13].

A further refinement of this DBS scheme is RECAT-PWS that consists in the determination of a static "Pair-Wise" regime, where each aircraft type pair has its appropriate wake turbulence separation minima, resulting in a pairwise distance table matrix. The distance-based PWS minima were initially determined for 96 aircraft types, frequent at European major airports and for which data are available to characterize the wake generation and wake encounter resistance [8].

B. Time-Based Separation concept

The TBS concept was developed by EUROCONTROL and NATS under the SESAR Programme. TBS provides a method for separating arriving aircraft by constant times instead of distances. It is based on a simple concept: in case of strong headwind, the time separation between a pair of aircraft for a constant distance increases compared to the time separation that would be needed between the two same aircraft in low wind conditions. The TBS concept maintains constant time separations between the aircraft across all wind conditions. It hence reduces their corresponding separation distances in strong headwind conditions.

The TBS concept improves the landing rate throughput and resilience to wind conditions on final approach through recovering and improving the lost landing rate currently experienced when applying DBS in strong wind conditions. This is achieved by defining the time separation minima between aircraft on final approach per aircraft type and independently of the wind conditions. Those reference time separations correspond to the time required for the aircraft to fly the reference DBS down to the separation delivery point in reference low wind conditions (typically less than 5 kts). The two inputs required to derive the reference time separations are therefore:
- A DBS wake separation scheme (e.g. ICAO, RECAT-EU, RECAT-PWS);
- The time-to-fly profiles in reference low wind conditions for all aircraft types. (Note that the reference time separation does not depend on the leader flight speed.)

As an example, using time-to-fly profiles measurements gathered in the framework of the RECAT-EU project, TABLE I provides the reference TBS applicable at runway threshold behind a large leader aircraft (ICAO Heavy and RECAT-EU CAT-B) and for the ICAO and RECAT-EU reference DBS schemes.

TBS has been deployed in London Heathrow in March 2015 providing significant benefits since then [14, 15].

TABLE I.   REFERENCE DISTANCE AND TIME SEPARATIONS BEHIND ICAO HEAVY AIRCRAFT / RECAT-EU CAT-B

Follower Aircraft	ICAO			RECAT-EU		
	Type	*DBS*	*TBS*	*Type*	*DBS*	*TBS*
A320	Medium	5 NM	124 s	CAT-D	4 NM	102 s
A318	Medium	5 NM	129 s	CAT-D	4 NM	109 s
AT72	Medium	5 NM	134 s	CAT-E	5 NM	134 s

C. Weather Dependent Separation concepts

The WDS concepts consist in the conditional reduction or suspension of distance- or time-based wake separation minima on final approach under pre-defined wind conditions, so as to enable runway throughput increase compared to the applicable standard weather independent wake separation minima. Those concepts are based on total or crosswind component and can be defined in time- or distance- based mode.

III.   SEPARATION SPACING INDICATORS

When applying either TBS or RECAT-PWS, air traffic controllers require indicators providing dynamic information on the spacing to be applied between aircraft pairs. Those indicators are the Final Target Distance (FTD), providing the separation minima, and the Initial Target Distance (ITD), providing an image of the expected compression. They depend on the expected aircraft speed profiles and headwind profiles. FTD and ITD also require to mitigate the risks deriving from uncertainties on aircraft performance and wind evolution.

A. Aircraft Speed

Since the only speed of interest for an aircraft flight dynamics is the speed with respect to the air, the aircraft ground speed may significantly vary depending on the head/tail wind conditions, as ground speed (GS) and True Air Speed (TAS) are linked to the headwind (HW) component through:

$$GS = TAS - HW \tag{1}$$

At this stage, it is useful to introduce the concept of time-to-fly (T2F). It is defined as the time required for the aircraft to travel a certain distance (X) to a separation delivery point (DP) (e.g., the runway threshold). It is thus related to the aircraft ground-speed through:

$$T2F(X) = \int_{DP}^{X} \frac{1}{GS(x)} dx \tag{2}$$

If the ground speed is constant, it is then simply obtained as the ratio between the distance to travel and the ground speed.

B. Final Target Distance

The first spacing indicator that the Air Traffic Controller (ATCO) requires is the FTD. It corresponds to the minimum separation applicable between two aircraft at the separation delivery point. For the FTD computation, a distinction should be made between time- and distance-based operations.

In distance-based operations (e.g., ICAO, RECAT-PWS, RECAT-EU), the FTD is simply equal to the distance separation defined for the considered pair (e.g., 5 NM when considering an A320 behind a large Heavy under ICAO or 4 NM under RECAT-EU). One then has:

$$FTD = DBS \tag{3}$$

In time-based operations, the FTD indicator should be computed such that the time separation, TBS, is applied between the considered pair (e.g., 124 s when considering an A320 behind a large Heavy under ICAO or 102 s under RECAT-EU in the examples of TABLE I). The FTD hence depends on the T2F profile of the follower aircraft in the prevailing headwind conditions through:

$$T2F(FTD) = TBS \tag{4}$$

Note that when separations between aircraft are reduced, wake separation could no longer constitute the relevant operational constraint. It is then important to also verify that the computed FTD still meets the following time- or distance based minima: Runway Occupancy Time (ROT) of the leader aircraft, Minimum Radar Separation (MRS) distance spacing, other time- or distance constraints due to airport infrastructure and modus operandi (e.g., custom wake scheme or dependent parallel runways). In case the computed FTD does not guarantee that these constraints are satisfied, it is increased following the same computation methodology but accounting for all other time and/or distance constraints. The separation delivery tool indicates to the ATCO which operational constraint is taken in account for the FTD calculation. This way the ATCO is aware of which FTDs are computed according to separation minima that shall not be infringed (e.g., wake separations) and which FTDs are computed according to other constraints (e.g., ROT) providing recommended spacing that should not be infringed.

C. Initial Target Distance

Because of the aircraft deceleration profile down to its final stabilized approach speed, because of the headwind profile and because of the differences in final stabilized approach speeds between leader and follower aircraft, catch-up/pull-away effects are observed between the leader and the follower aircraft between the glide and the separation delivery point. The separation to be applied on the glide hence corresponds to the FTD increased by a buffer accounting for the expected compression. In today's air traffic control environment, these compression buffers are estimated directly by the air traffic controllers based on their operational experience of the aircraft performances in the observed wind conditions. When applying dynamic pair-wise separation (using e.g., TBS or RECAT-PWS), due to the significant variation in applicable separation minima, the compression buffers can no longer be accurately estimated by the controllers. There is thus a need for a separation support tool to also provide this information.

The ITD indicator provides the distance separation applicable when the leader aircraft is at a prescribed speed (e.g., 160 kts) at a prescribed position x_{ITD} (e.g., 5 NM from the runway threshold) and such that a separation equal to the FTD will be delivered at the separation delivery point. An example of the ITD progression is provided in Fig. 1. The inputs for the ITD computation are thus: the FTD computed above, the follower speed profile, the leader speed profile and the headwind profile. It is computed using the leader and follower time-to-fly profiles through:

$$T2F_{foll}(x_{ITD} + ITD) - T2F_{foll}(FTD) = T2F_{lead}(x_{ITD}) \tag{5}$$
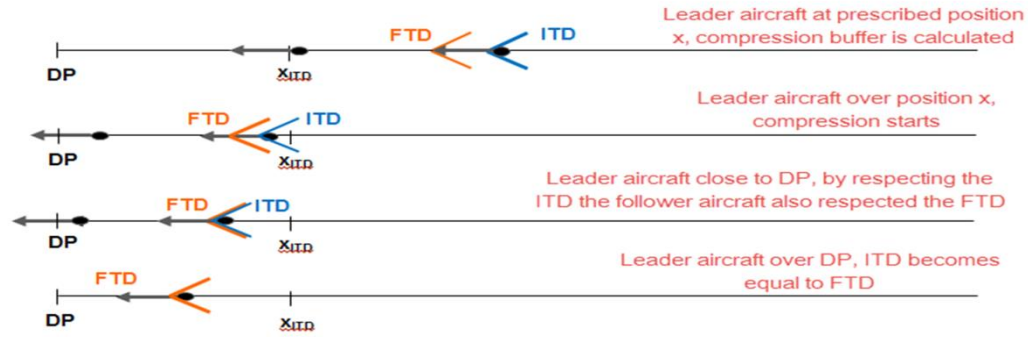
Fig. 1 Schematic view of ITD and FTD indicators

D. Mitigating uncertainties

To be of use for the air traffic controller, the FTD and ITD indicators have to be available for display in advance: once the sequence order is established and before the follower is positioned on the glide. The indicators have hence to be computed based on an assumed aircraft performance model and forecast headwind conditions. Typically, for approach, considering that the aircraft flies at 160 kts on the glide for 15 NM and assuming that the separation has to be computed when the aircraft flying at 200 kts is at 20 NM from the glide, the time horizon of interest is around 10 to 15 minutes.

Both FTD and ITD are computed using the aircraft time-to-fly profiles. An error in the airspeed profile and/or in the headwind profile used to compute the time-to-fly profile, introduces errors in both the FTD and ITD computations. To reduce this uncertainty, when using separation indicators, the aircraft pilots are instructed by the controllers to maintain a constant glide airspeed (typically 160 kts) before decelerating to their final approach speed once the aircraft is close to the ITD. However, because of the uncertainty on the headwind and on the aircraft flight speed deceleration profiles, safety buffers have to be added both in the FTD and ITD indicator computations.

For the FTD computation, a distinction should again be made depending on time- or distance- based operations. For distance-based operations, the FTD does not depend on the aircraft performances, neither wind nor safety buffer shall then be added. On the contrary, in time-based operations (e.g., in TBS mode or when ROT is the relevant spacing), a buffer shall be added in the FTD computation such that if the FTD separation is applied, the time separation minimum will be observed regardless of the aircraft performance model and forecast uncertainties. These buffers shall be computed to cope with wind uncertainties (i.e., measurement accuracy and natural wind variation) and follower speed uncertainty.

For the ITD computation, safety margin have also to be added, regardless of time- or distance-based operations such that if the follower is positioned at the ITD separation and at the prescribed glide slope speed when the leader is positioned at x_{ITD}, the FTD separation will be observed at the separation delivery point. It shall be able to cope with wind uncertainties on the complete glide (measurement accuracy and natural evolution) and with both leader and follower speed profile uncertainties.

The safety buffers should be designed for an "acceptable" under-spacing rate (i.e., typically, the rate of under-spacing as observed in today's environment). This last point is of primary importance. Indeed, aiming for zero under-spacing in the safety buffer design would significantly increase the safety margins and hence significantly reduce the capacity benefits related to the use of the improved separation scheme. Using the FTD and ITD, ATCOs will have to observe flight tracks and take actions to avoid under-spacing situations. These observations are similar to today's observation of compliance with separation minima values.

TABLE II summarizes the main sources of uncertainties for FTD and ITD computation in time- and distance-based modes.

TABLE II.   SOURCES OF UNCERTAINTIES FOR FTD AND ITD COMPUTATION IN TBS AND DBS MODES

	TBS/ROT	**DBS/MRS**
FTD	• Follower final approach speed • Follower deceleration point • Headwind on final	• None

ITD	- Follower final approach speed - Leader final approach speed - Follower deceleration point - Leader deceleration point - Headwind on final - Headwind on glide

The separation buffers to be applied on the FTD for a time-based separation (e.g. in TBS mode or for a ROT spacing constraint) and on the ITD (in all modes of separation) can be expressed as a time buffer ΔTBS to be added in the indicator computation. It reads:

$$T2F(FTD) = TBS + \Delta TBS_{FTD}, \text{ and} \tag{6}$$

$$T2F_{foll}(x_{ITD} + ITD) - T2F_{foll}(FTD) = T2F_{lead}(x_{ITD}) + \Delta TBS_{ITD} \tag{7}$$

The design of these time buffers are based on an extensive measurement data analysis, using the speed profiles characterized down to the separation delivery point in all different headwind conditions and for each aircraft type. Those data are obtained, e.g., through RADAR tracks combined with a wind speed vertical profiler, or Mode-S data.

For the FTD buffer computation, for each range of headwind conditions, all aircraft measured in such headwind conditions are combined in pairs and a separation equal to the FTD (computed with a buffer) at the separation delivery point is applied. The obtained time separations are then compared to the time-based minima. The FTD time buffers are then adapted, in an iterative procedure, until an accepted "failure" under-spacing rate is obtained. Note that the accepted failure rate might depend on the reason behind the FTD separation. One can for instance accept a different failure rate for a wake separation than for a runway occupancy time under-spacing. Note also that for stronger wind conditions, it has been shown that the positive effect of the wind on the wake decay allows for time separations even lower than the TBS minima [16]. For stronger wind conditions, FTD time buffers will hence also be reduced.

The design principle of the ITD buffer computation is similar to that of the FTD. For each range of headwind conditions, all aircraft measured in such headwind conditions are combined in pairs and a separation equal to the ITD (computed with a buffer) at the ITD reference point x_{ITD} is applied. The separations obtained at the separation delivery point (i.e., after compression) are then compared to the FTD (computed with the above determined buffers). The ITD time buffers are then progressively adapted, in an iterative procedure, until an accepted "failure" under-spacing rate is obtained. Using Mode-S data, typical buffer values of about 1.5 s and 10 s are seen to be needed for ΔTBS_{FTD} and ΔTBS_{ITD} respectively.

IV. DESIGN AND VALIDATION OF LORD PLATFORM

TBS or RECAT-PWS would be too challenging for the ATCOs to apply without separation spacing indicator information displayed on their Controller Working Positions (CWPs). A demonstrator of such a separation delivery support tool for ATCOs was developed by EUROCONTROL and partners in the SESAR 6.8.1 project. It provides the FTD and ITD indicators, computed using the above described methodology to determine adequate buffer based on operations, failure rate and wind conditions. This platform is named LORD.

Through its HMI, LORD tool indicates to the ATCO the optimum position of the follower aircraft on the glide, facilitating the management of the appropriate separation and spacing buffers between the aircraft pair. For the computation of the separation minima it takes as input:
- The speed profile of the leader aircraft
- The speed profile of the follower aircraft
- The wind profile
- The wake separation scheme (e.g. ICAO, RECAT-PWS) and mode (DBS or TBS)
- The expected ROT of the leader aircraft

The aircraft speed profile models in the tool are calibrated and benchmarked against extensive RADAR and Mode-S data. These data were collected by EUROCONTROL and partners in different previous wake activities.

Once the separation minima for a given pair are computed, the resulting outputs are the two target distance indicators (TDI): FTD and ITD. The two TDIs are then displayed on the extended runway centerline of the final

approach controller's radar display and the tower runway controller's air traffic monitor display. The TDIs that are represented as chevrons on the HMI are shown in Fig. 2.

By default, the approach controller only displays the ITD on the CWP. He can however also trigger the display of the FTD to evaluate the compression buffer (visualized by the difference between the ITD and the FTD chevrons). The tower controller mainly works with the FTD allowing him to ensure that the separation minima are respected between landing aircraft.

A. Support Warnings

The European Commission regulation "PCP" No 716/2014 defines functionalities that need to be put in place when operating the TBS solution. These functionalities include warnings like detection and alerting in case of catch-up on approach, separation minima infringement and wrong sequence order. Therefore, in addition to the spacing indicators, the LORD provides support warnings for the ATCO. These warnings have to be used as safety nets to quickly identify potential issues in the approach/landing phase.
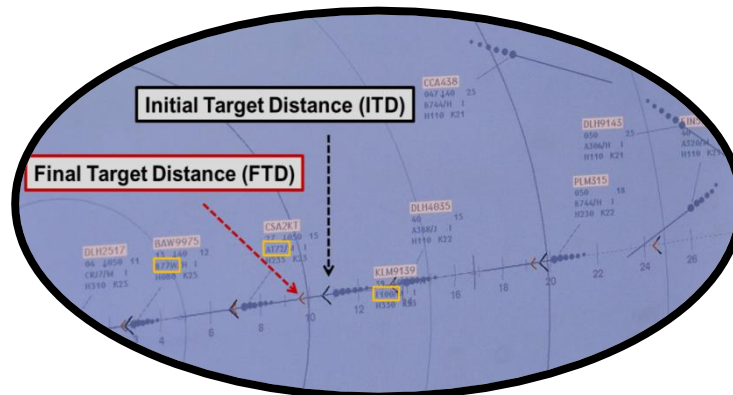
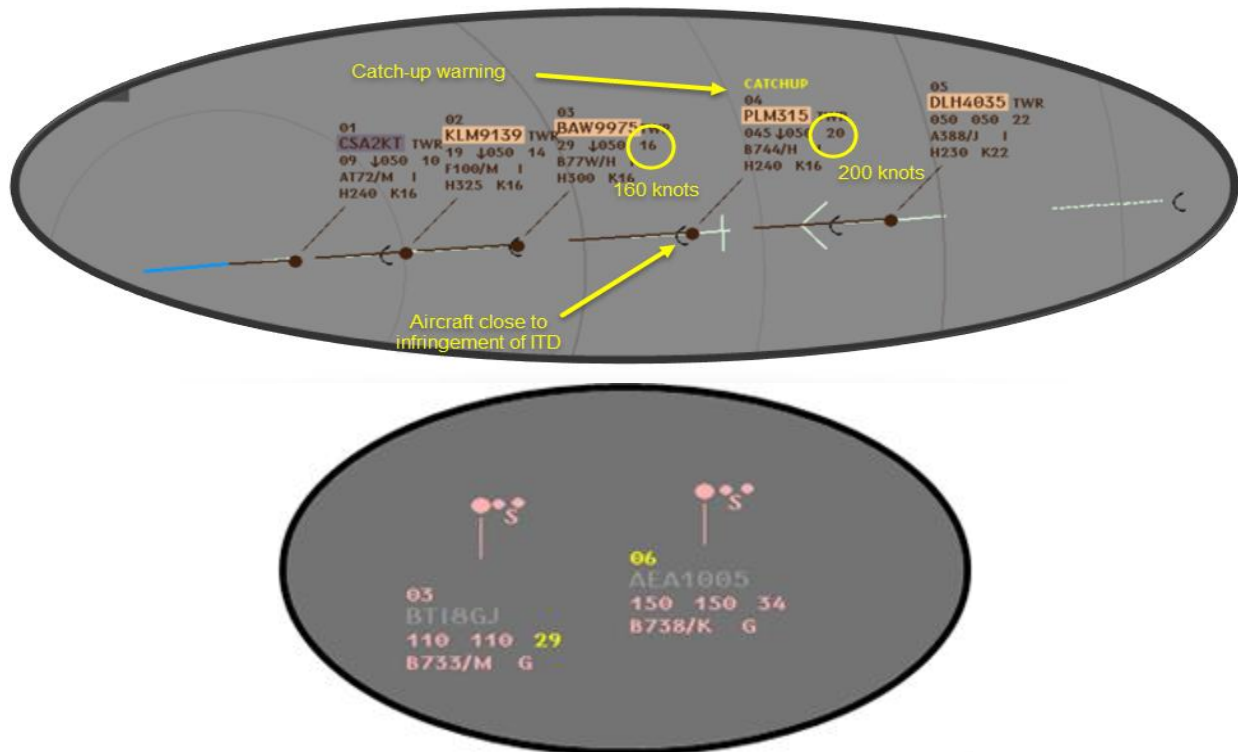

Fig. 2 FTD and ITD chevrons displayed on the LORD HMI

Fig. 3 Catch-up (top), sequence and speed conformance (bottom) warnings displayed on the LORD HMI

1. Catch-up warning:

In normal operations, once on the glide and with correct separations imposed, the controller should instruct pilots to reduce the aircraft speed to 160 knots. In the situations where he can still reduce the over conservative spacing between aircraft, he can allow the follower aircraft to fly faster for a certain period.

The catch-up warning (illustrated in Fig. 3) activates when the follower aircraft is getting close to the ITD and is flying faster than the leader aircraft. In this catch-up situation, the follower speed has to be reduced so as to avoid ITD "infringement" in the next future. In the LORD HMI, this alert is visualized through a label with the word 'catch-up' in yellow, displayed above the aircraft radar label. However, it should be noted that the controller should not use the catch-up warning as means to know when he should give the instruction to the follower aircraft to reduce to 160 knots. In other words, this warning shall not be used tactically by the ATCO for speed management on final approach.

2. Speed conformance

This warning activates when the aircraft is flying at a much higher/lower speed than what is expected in the modelled speed profile used by the LORD tool for the FTD and ITD computation. In time-based separation operations (i.e., in TBS or for a ROT separation), if the aircraft does not comply with the expected speed profile, the computation of the distance spacing indicators obtained from the conversion of the T2F in distance might not be correct and misleading for the ATCO. Even though a mitigation safety buffer has been included in the FTD and ITD computation, a too large deviation might lead to a time separation infringement whereas the displayed FTD chevron is not infringed.

In the LORD HMI, when the warning is active, the speed information on the radar aircraft label is highlighted in yellow (see illustration in Fig. 3). The warning disappears when the aircraft returns within the expected speed profile boundaries.

3. Sequence Pairing and sequence alert

In the LORD HMI, the aircraft selected by the ATCO is automatically highlighting the corresponding moving chevron. This allows the ATCO to quickly identify whether a wrong aircraft has been inserted in the sequence. He can then update the aircraft sequence precomputed by the system according to his needs. How the sequence is maintained, manually by the ATCO or automatically by the system, is a technical choice that depends on the single airport environment. There are airports with only few STARs and TMA approaches with strict procedures, in these environments it is easy to understand which aircraft belongs to which part of the sequence, the tool can automatically recognize the sequence and will maintain it updated on his own. There are other airports with a higher number of runways, different aiming points for approaches, where the final decision on which runway the aircraft should land, and in which order, is left to the ATCO. In these situations it will be the ATCO responsibility to maintain the correct sequence up to date in the system. A sequence alert detecting automatically wrong sequencing of the aircraft on the glide can also then be used. In the LORD HMI the wrong sequence number is highlighted in yellow (see Fig.3) and it disappears when the aircraft receives the correct sequence number input by the ATCO.

4. ITD Separation Infringement

In the situations where, despite the catch-up warning, the aircraft "infringes" the ITD, the FTD is automatically displayed on the extended runway centerline of the CWP (Fig. 4). It is important to recall that an ITD "infringement" is not a loss of separation since the ITD does not represent the separation minimum. This warning allows the controller to notice the ITD infringement, evaluate how much compression buffer is left before a FTD infringement (which would then be a loss of separation or under-spacing) and if he has enough margin for recovery actions (e.g. to slow down the aircraft). As explained before (see Section III D.), the ITD is computed with an additional buffer to prevent FTD infringement, which means that a small infringement of the ITD does not lead automatically to an infringement of the FTD if no actions are taken. In fact, in nominal operations (i.e., when the aircraft speed profile are conform with those used in the LORD FTD/ITD computation model), if the follower is on the ITD chevron before the leader deceleration, a small buffer compared to the FTD chevron will be observed at the separation delivery point.
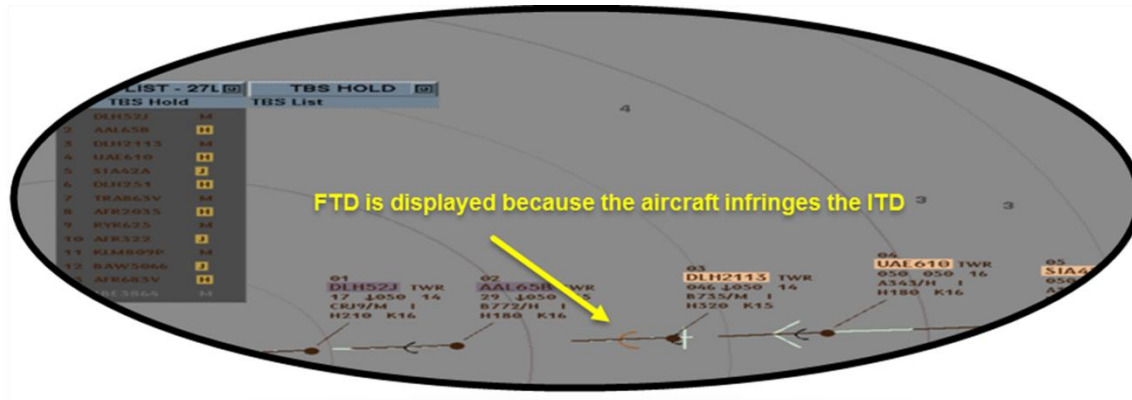
Fig. 4 ITD Separation Infringement leading to automatic FTD display

B. Operational Results and Feedback

1. SESAR 1 – THALIN 2 for Paris Charles De Gaulle Airport environment – February 2016

EUROCONTROL, together with THALES and DGAC-DSNA performed a Real-Time Simulation (RTS) campaign with controllers that operate at Paris- Charles De Gaulle (CDG) Airport. Using peak hours traffic and the ICAO distance-based separation scheme as baseline, the LORD tool was tested with the ICAO TBS and RECAT-PWS DBS solutions in different wind conditions, the full report that describes the context of the validation, the validation objectives, the scenarios and the RTS results is part of the SESAR 1 P6.8.1 Deliverables [17]. A synthesis of the results is presented in this section. The capacity results, illustrated in Fig. 5, show that TBS (using the LORD tool) allows the recovery of part of the capacity loss due to strong wind condition. RECAT-PWS solution is observed to lead to higher throughputs compared to ICAO in all wind conditions.
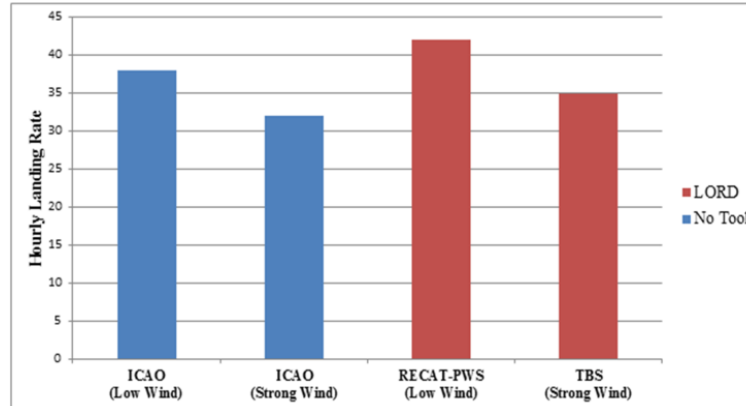

Fig. 5 Comparison of the measured Throughput in THALIN 2 RTS campaign for CDG airport environment (from left to right): ICAO DBS low wind, ICAO DBS strong headwind, RECAT-PWS DBS with LORD tool low wind, ICAO TBS with LORD tool strong headwind

In addition to the increased runway throughput, a reduction in the number of aircraft spaced below the separation minima was also found when using the LORD tool, with positive impact on safety. For making this comparison, the results of RTS were benchmarked to real separation data from the Optimized Runway Delivery study [18] at CDG airport when ICAO separations scheme was still in place in 2015. For each leader-follower pair ICAO wake turbulence category (i.e. Heavy-Heavy, Heavy-Medium, Medium-Heavy, Medium-Medium), the rate of under-separation observed for the "constrained" pairs (i.e. close to separation minima) is recorded. The total rate of under-spacing is then obtained by weighting the under-spacing of each pair category (whilst aligning the rates of under-spacing for A380 on Heavy data) by the RTS traffic mix. The resulting percentages of pairs within different ranges of under-separation are presented in TABLE III.

Category (separation buffer)	Metric	ICAO (CDG operations)	RECAT PWS
Pairs with no under-separation.	Number (Percentage) of Pairs	92.2%	94%
Pairs with max 0.25Nm under-separation.	Number (Percentage) of Pairs	4.4%	3.8%
Pairs within 0.25 to 0.5Nm under- separation.	Number (Percentage) of Pairs	2.3%	0%
Pairs with more than 0.5Nm under- separation.	Number (Percentage) of Pairs	1.1%	0%
Go-around aircraft	Number of Go-arounds (Percentage of Pairs)	Unknown	2.2%

During the RTS campaign, a Human Performance study was also performed. The results showed that the workload, situation awareness, procedures and working method were considered as acceptable by the Final Approach and Tower controllers when using RECAT-PWS DBS and ICAO TBS with the LORD tool. A high level of trust and confidence was observed for the concepts, the HMI and support warnings. The EUROCONTROL SHAPE Automation Trust Index (SATI) was used to assess controller trust and confidence in the TDIs / support warnings and a bespoke utility & usability questionnaire was developed specifically to assess the utility and usability of the TDIs / support warnings. Both the SATI and utility & usability questionnaires were completed by the controllers working the Final Approach and Tower positions. The mean overall SATI trust scores for the ITD for the Final Approach and Tower controllers were high, with the mean overall score for the TDIs being 4.97 and 5.58 out of a maximum of 6. The Final Approach and Tower controllers' trust and confidence in the TDIs was above the acceptable lower limit of 4.5. Analysis of the individual controller scores for each SATI statement showed that the majority of controllers felt that the TDIs were useful, reliable, worked accurately, were understandable, worked robustly in difficult situations and were confident working with the ITD.

2. SESAR 1 – THALIN2 for Vienna Schwechat Airport environment – April 2016
Following this RTS, an additional simulation was conducted to demonstrate the application of the same concepts in the Vienna approach and tower environment with AUSTROCONTROL ATCOs (see Fig. 6). The aim of the simulation was to demonstrate the feasibility of applying the concepts and the support delivery tool in the Vienna approach environment under a variety of wind conditions and to assess whether the changes introduced by the concepts and the separation delivery tool were acceptable to the Vienna final approach and tower controllers. Two separation schemes were applied in the simulation: ICAO DBS, as in current day operations, and RECAT PWS using TBS. Two different wind scenarios were tested, a low wind and a strong wind scenario, with respectively 0.5 knots and 25 knots on the ground. Two different traffic samples were developed based on real data from Vienna airport traffic. A full description of scenarios, traffic samples and results of the RTS is part of the SESAR1 Project 6.8.1 deliverables [17].
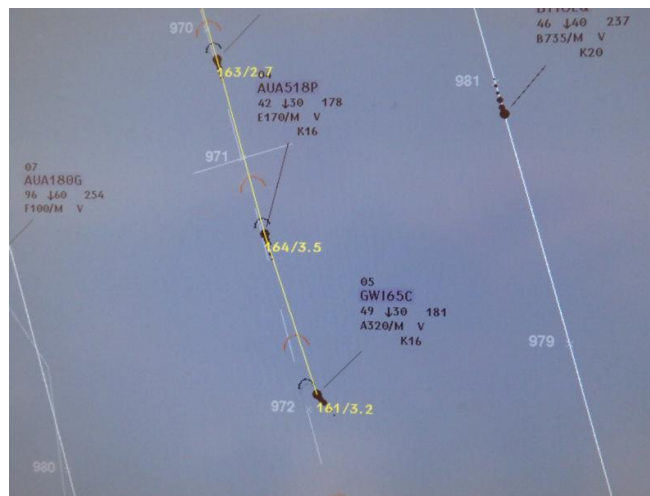

Fig. 6 –VIENNA RTS Approach controller working position showing RECAT-PWS and the LORD tool (FTD depicted as arc on final approach in red, ITD depicted in black)

In the results both the Final Approach and Tower controllers reported to find it easy to work under RECAT-PWS with the LORD tool, and were found to be able to quickly adapt to the new working methods using the TDIs and the reduced separation minima. Benefits in terms of increased throughput were observed in low and strong wind conditions (see Fig. 7).
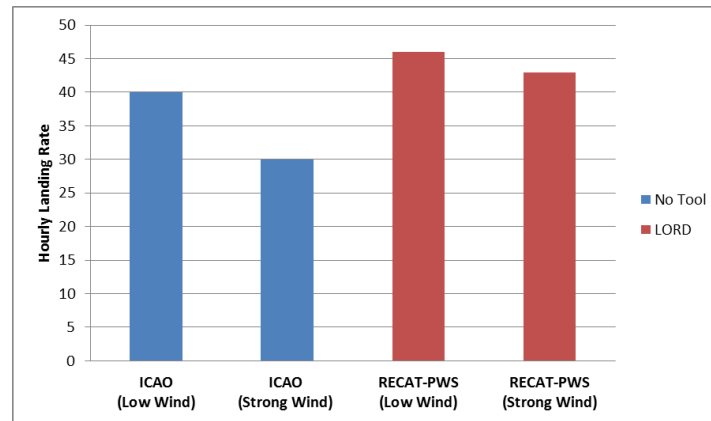

Fig. 7 Comparison of the measured Throughput in THALIN 2 RTS campaign for Vienna airport environment (from left to right): ICAO DBS low wind, ICAO DBS strong wind, RECAT-PWS TBS with LORD tool low wind, RECAT-PWS TBS with LORD tool strong wind

3. SESAR 2020 - THALIN 3 for Paris Charles De Gaulle Airport environment – September 2017

Building on the validation activities conducted in SESAR 1, five additional RTS campaigns are currently planned in the framework of SESAR 2020 to further improve the separation support tool. The first campaign was completed in September 2017 with DGAC-DSNA ATCOs. The aim was to further assess and test the tool in the Paris-CDG airport and approach environment using two parallel independent runways (divided in North and South operations, see Fig. 8), and with the WDS concept. The RECAT-EU DBS wake scheme without the support delivery tool was used as baseline (since it corresponds to current operations in Paris-CDG).

Fig. 8 –THALIN 3 RTS CDG South Approach controller working position showing WDS and the LORD tool (FTD depicted as arc on final approach in red, ITD depicted in black/green when paired to aircraft call sign)

This RTS focused on the WDS crosswind concept, where the wind is sufficiently strong to enable the wake turbulence separations to be completely relaxed for almost all aircraft pairs on the final approach, so that for those pairs the aircraft separation minima are the Minimum Radar Separation (MRS=2.5 NM) unless runway occupancy time is the greatest constraint. The arrival traffic samples were designed with 43 arrivals per hour (approximately

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10% more than today's maximum of 39 arrivals per hour on Runway 27R) with a mix that corresponds to an extrapolation of what is expected be the traffic at Paris-CDG in the next 5 years.

The runway throughput in the exercise runs with WDS and the LORD tool was found to be higher than in the reference scenario, i.e. RECAT-EU with no tool. The runway throughput values measured in the different exercises for the Runway 27 R used for the north operations are provided in Fig. 9.
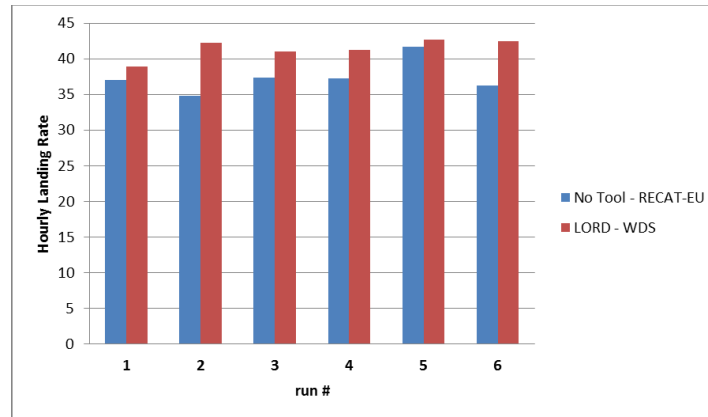

Fig. 9 Runway throughput for arrivals for North sector operations (Runway 27R) for baseline (blue) ad solution scenarios (red)

For both North and South operations the number of minor under-separated aircraft flights (less than or equal to 0.5 NM but more than 0.1NM) on the final approach was found to be lower under the exercises with WDS and the LORD tool compared to the reference scenario, i.e. RECAT-EU with no LORD tool exercises. Moreover, the number of major under-separated aircraft (more than 0.5NM) on the final approach was found to be lower for South and the same for North operations in WDS with tool runs compared to the reference scenario.
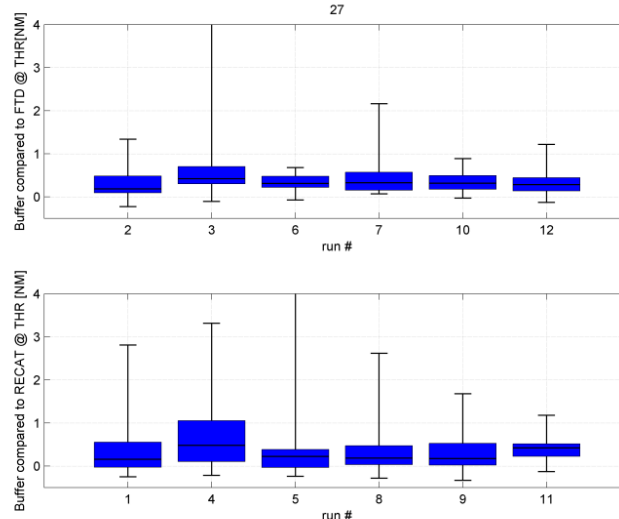

Fig. 10   Quartile plots of separation conformance to separation minima for the various runs for North sector operations (Runway 27R): WDS with tool (top) and RECAT-EU without tool (bottom)

Fig. 10 illustrates for North operations the separation conformance to the minima delivered by the ATCOs. It is expressed as the measured buffer above the separation minima for the follower aircraft when the leader aircraft was at threshold. Median separation buffers were seen to be equivalent when applying either RECAT-EU without tool or WDS with the LORD tool: they ranged from 0.15 up to 0.48 NM for the RECAT-EU cases (excluding run 4), whereas they ranged from 0.18 up to 0.42 NM for the WDS cases. However the range of variation around the mean value is seen to be more limited when applying WDS with the LORD tool.

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In the small under-spaced pairs (i.e. those with under-spacing values lower than 0.5 NM), when applying RECAT-EU with no tool, 0 to 5 % of the pairs were found with under-spacing larger than 0.25 NM whereas no such cases were found for the WDS with LORD tool runs. All small under-spaced pairs of the WDS with the LORD tool runs had thus an under-separation of at most 0.25 NM.

It is also interesting to note that, for the success pairs (those with max under-spacing of 0.1 NM), 52 to 79 % of those pairs were delivered with a buffer of maximum 0.5 NM when applying RECAT-EU and 55 to 83 % when applying WDS with the LORD tool.

The ratings obtained from the SATI questionnaire (Fig. 11) showed that the controllers had a good level of trust in the LORD tool when working in all the different positions. Controllers reported positively that they found the tool to be useful, reliable, accurate, and understandable and that it was found to work robustly in difficult scenarios. All controllers reported in the SATI questionnaire that they felt confident when working with the tool.
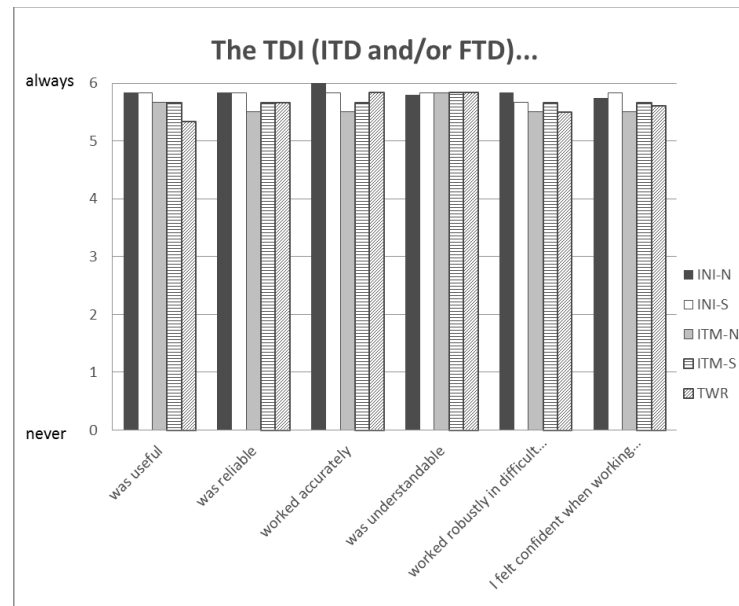

Fig. 11   Average ratings for Trust on the SATI questionnaire

V.   CONCLUSIONS AND NEXT STEPS

In the recent years, new solutions were developed for aircraft traffic separation management. They allow for dynamic wake separation reductions depending on aircraft characteristics and weather conditions. TBS, RECAT-PWS and WDS belong to this set of new separation concepts. However, the application of such dynamic separation solutions requires the use of a tool supporting the air traffic controller in the safe separation delivery task. This tool shall compute the applicable time- or distance based separation minima and provide other indicators and alerts supporting their correct delivery by the controller.

In this paper design principles for such a separation support tool allowing optimized runway delivery were presented. These principles were used for the development of a demonstrator by EUROCONTROL, called the LORD tool. The tool and its HMI facilitate the separation delivery when new wake concepts like TBS, RECAT-PWS or WDS are applied by the ATCO in constrained airports environments. It provides the distance separation minima, named Final Target Distance, and is complemented by an indicator to manage spacing buffers, named the Initial Target Distance, and by support warnings for a faster detection of potential issues. In addition, the LORD tool makes use of a methodology to mitigate separation infringements and to prevent aircraft under-spacing by using an additional buffer on the ITD and FTD computation, accounting for wind forecast and aircraft performance uncertainties. The use of such a buffer allows the separations to be correctly delivered up to a certain 'failure rate' equivalent to what is currently observed at airports. It also provides capacity benefits with a better spacing management performed by the controller in different separation modes (distance- or time based).

The LORD tool was successfully tested by Air Traffic Controllers during Real-Time Simulation campaigns in two different airport and airspace environments. The use of the new separation concepts together with the LORD tool resulted in an increase of throughput and a reduction of separation infringement, while maintaining workload and situation awareness at an acceptable level.

For the future, in the SESAR 2020 Project 02, there is a considerable amount of activities aiming to improve the LORD tool, extending its use to departures, mix mode, closely-spaced parallel runways, with integration of enhanced approach procedures in the landing sequence, together with the new wake solutions like the WDS. The development will allow the LORD tool to use different sets of solutions at the airport, thus adapting to the real-time situation and making possible a smooth transition from one operating condition to another (e.g. from TBS to WDS).

Finally, a higher accuracy of the separation tool indicators could also be reached using Big Data/Machine Learning techniques. The use of such methods could allow for dynamic buffer reductions based on all parameters influencing the aircraft speed behavior (wind, aircraft type, airlines, temperature, etc.) and hence the ITD and FTD computation. A reduction in the used buffers would allow further optimization of the traffic sequence and spacing, with direct impact on runway throughput and related benefits.

Acknowledgments

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