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Improved Configuration Management for Greener Approaches – Evaluation of a Novel Pilot Support Concept

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Abstract

Carrying out a safe approach under fluctuating wind and weather conditions while following air traffic control (ATC) instructions imposes a significant workload on the flight crew, especially with the limited systems support and information availability on the flight deck today. Individual skills of the pilots including correct anticipation of the weather situation and ATC instructions are necessary to manage speed and configuration changes of the aircraft in an optimal way. Consequently, approach operations at busy airports are virtually always noisier and less fuel efficient than technically possible. The DYNCAT project's access to all relevant data sources (on-board operational data, ATC commands, noise measurement data, surrounding traffic and weather information) allowed to evaluate individual approach operations in their full context, exemplarily for the Airbus A320 at Zurich airport. Based on this analysis, an operational concept was developed to support pilots and controllers through extended information exchange, thus increasing predictability of the lateral and vertical flight profiles for both sides. A central component is a novel airborne energy management assistance system including a configuration management functionality, implemented through an extension of the Flight Management System (FMS) capabilities. Piloted simulator trials on a fixed-based test bench were performed to evaluate the effects of the latter not only on fuel burn and noise exposure levels but also on pilots' workload and situational awareness. The present partial and initial implementation of the function for the Airbus A320 family evaluates favourably with respect to the above criteria when compared with the state of the art.

Keywords: aircraft energy management; fuel saving; noise abatement; flaps and landing gear management; pilot assistance system

1. Introduction

Approach operations at busy airports face conflicting requirements from different sides: Air Traffic Management (ATM), on the one hand, needs to simultaneously manage the operation of many aircraft safely (maintaining minimum separation at all times) and efficiently (ultimately maximising arrival and departure rates). Controllers thus often need to use intermediate level-off and speed instructions to ensure separation – also with departing traffic.

On the other hand, safe and efficient landing operations of the individual aircraft from the pilots' view follow procedures laid down by the aircraft manufacturer and aircraft operator in the Flight Crew Operating Manual (FCOM). It means following a sequence of configuration changes (extension of the high-lift system in several steps, extension of the landing gear) with associated changes in airspeed. These are highly specific, depending not only on the type of aircraft, but also on its current weight and the wind situation along the flight path. The management of configuration and the speed regime are dependent on each other. Current state of the art of airborne noise abatement is the Continuous Descent Operations (CDO) concept that minimises fuel consumption and engine noise by flying from the top of descent (ToD) down to the final approach at near idle power [1]. Airlines are under great pressure regarding cost efficiency, hence minimum fuel consumption is a major consideration for them besides safety. Engine fuel flow is not negligible in idle and obviously many direct operational costs are dependent on the flight time, which tends to favour higher speeds during approach, being generally detrimental to noise emission.

A very critical issue during approach and landing is managing energy, consisting of potential (altitude) and kinetic (speed) components. If the energy level is too low for the intended flight profile, thrust needs to be raised beyond idle, easily achieved but increasing noise and fuel burn. On the other hand, if the descent is initiated too late or intermediate approach speeds are too high, the high aerodynamic efficiency of modern airliners renders the reduction of this excessive energy level until touchdown problematic. Where the (noise-intensive) use of airbrakes is not sufficient, difficulties will arise in stabilising the approach, which is a direct safety concern. Practical countermeasures range from relaxing ATC restrictions to waiving the FCOM's recommendations and performing configuration changes at higher airspeeds in order to increase drag and hence the deceleration potential of the aircraft. This does not only accelerate structural fatigue but unnecessarily increases noise, thrust, fuel consumption and generation of CO_2 and other pollutants [2].

Current FMS offer very limited support for fulfilling the requirements and recommendations in the FCOM outside the nominal case. Hence in the real world, in the presence of ATC (altitude / speed / lateral) constraints and with the actual wind situation, the optimisation of the configuration sequence depends on the pilots' skills and their access to the necessary information.

The present paper summarises the findings of the SESAR Exploratory Research project DYNCAT ("Dynamic Configuration Adjustment in the TMA" (Terminal Manoeuvring Area)) [3] which was established to improve this situation. In the following section 2, a short overview of the analysis of the current operations is given as motivation for the development. The potential for improvement is analysed in section 3. Section 4 describes the DYNCAT operational concept which aims at reducing the unnecessary environmental impact resulting from the current mismatch between ground and airborne procedures and also lack of support mainly on the airborne side. The core of this operational concept, a new FMS and CDS (Cockpit Display System) functionality supporting the flight crew in energy and configuration management, is implemented in a test bench (as described in section 5) and evaluated in piloted simulations regarding operational and environmental improvements (section 6). The evaluation quantifies which improvements in CO_2 reduction and noise footprint could be possible with short-term (mainly on-board procedures) and mid-term (mainly new on-board system functionalities) measures.

2. Exemplary Analysis of the Current Situation

Virtually all real-life approaches deviate from the theoretically possible in terms of noise and fuel consumption minimisation under the respective circumstances. This may on one hand be due to operational necessities from ATC (e.g. airspace structure, separation requirements), but there are also many suboptimal situations which are only a consequence of lack of information: on ATC intentions including the expected distance-to-go (DTG) and the wind situation along the approach profile on board, and on the specific aircraft's capabilities and limitations as well as the wind situation in the TMA on ground. Additionally, there is insufficient systems support in trajectory and flight state prediction on the flight deck, so that pilots tend to configure more conservatively with unfavourable consequences on noise and fuel consumption. A critical analysis of the current situation has been performed in an exemplary way [4][5]. The Airbus A320-214 has been used as reference aircraft type and Zurich airport as reference airport, representing a very common aircraft type and a busy commercial airport with a complex airspace structure.

667 data sets for the selected target runway (RWY) 14, fulfilling the requirements of aircraft type and representing a broad variety of operational and weather conditions, were chosen from the Flight Data Monitoring data bases (Figure 1). These onboard data were matched and combined with all relevant ATC communications, radar, weather and noise parameters including information on surrounding traffic, yielding comprehensive data sets describing one approach operation each in its full context.

The evaluations performed in [5] are a unique opportunity to analyse the impact of ATC instructions on fuel consumption and noise exposure. Zurich is particularly suitable for this investigation because runway 14 does not have an area navigation (RNAV) transition, which means that lateral flight guidance takes place entirely on the basis of ATC directional instructions (open-loop procedure).

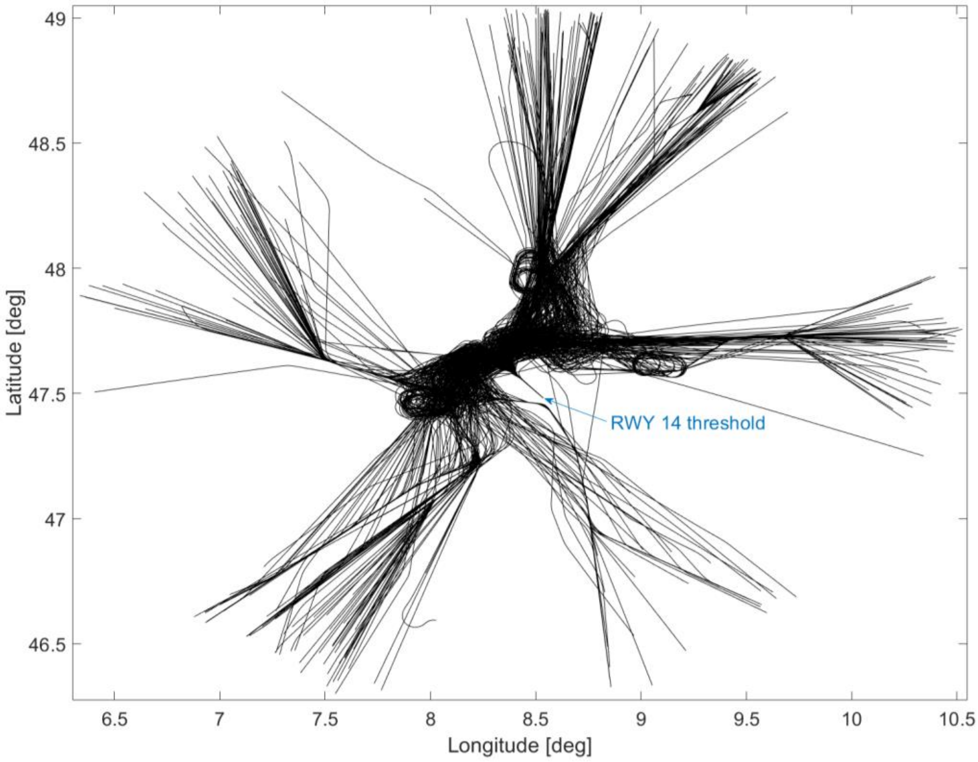

Figure 1 – Lateral flight paths (top view of ground tracks) of all 667 Airbus A320 flights into Zurich airport investigated for the analysis. The depicted tracks begin at Flight Level (FL) 100 and end at the threshold of the target runway 14, which can be seen in the centre of the figure.

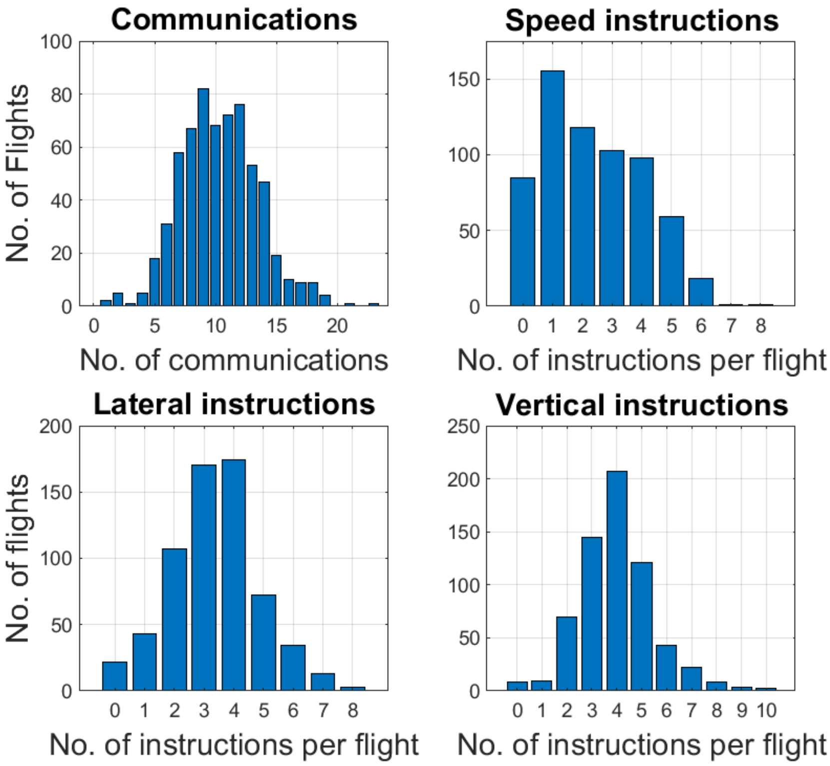

Figure 2 – Distribution of number of received radio calls per flight from the arrival controller: all received communications (upper left); communications related to speed (upper right); communications related to the lateral flight profile (lower left); communications related to the vertical flight profile (lower right).

In Figure 2 an overview of the overall number of ATC arrival (voice) communications and also of the three typical instructions categories (lateral, vertical and speed instructions) is shown (the depiction excludes communications originated by the pilots; only outgoing communications from ATC are represented). In the upper left plot, it can be seen that a large number of flights perform descent and approach phases under frequent communication with the arrival controller; for instance, 82 flights have nine communications received from ATC. With respect to speed restrictions, as can be seen in the upper right plot, there is a significant number of flights that receive no speed instruction, about 85 flights. On the other hand, the maximum number of speed instructions found in the ATC communications for a single approach was eight. The lower left plot shows the distribution of the number of lateral instructions. Very few flights have no lateral instruction (~3%), whereas the majority of flights receive at least three lateral instructions. The same picture can be seen on the lower right plot, where three or more vertical instructions are standard for the investigated flights.

Figure 3 presents an example synthesis of one typical flight with unsuitable speed constraints for the Airbus A320. The usage of speed brakes in clean configuration is limited when the aircraft is flying close to the minimum clean speed. However, in order to comply with the descent instructions, the deployment of speed brakes is necessary. As a consequence, the pilots have to extend Flaps 1[1] early to achieve a sufficient margin from the actual speed to the lowest selectable speed (VLS) and to stay within the speed limits when using speed brakes. Due to the higher noise emission with extended high-lift devices versus clean configuration, the former is significantly increased.

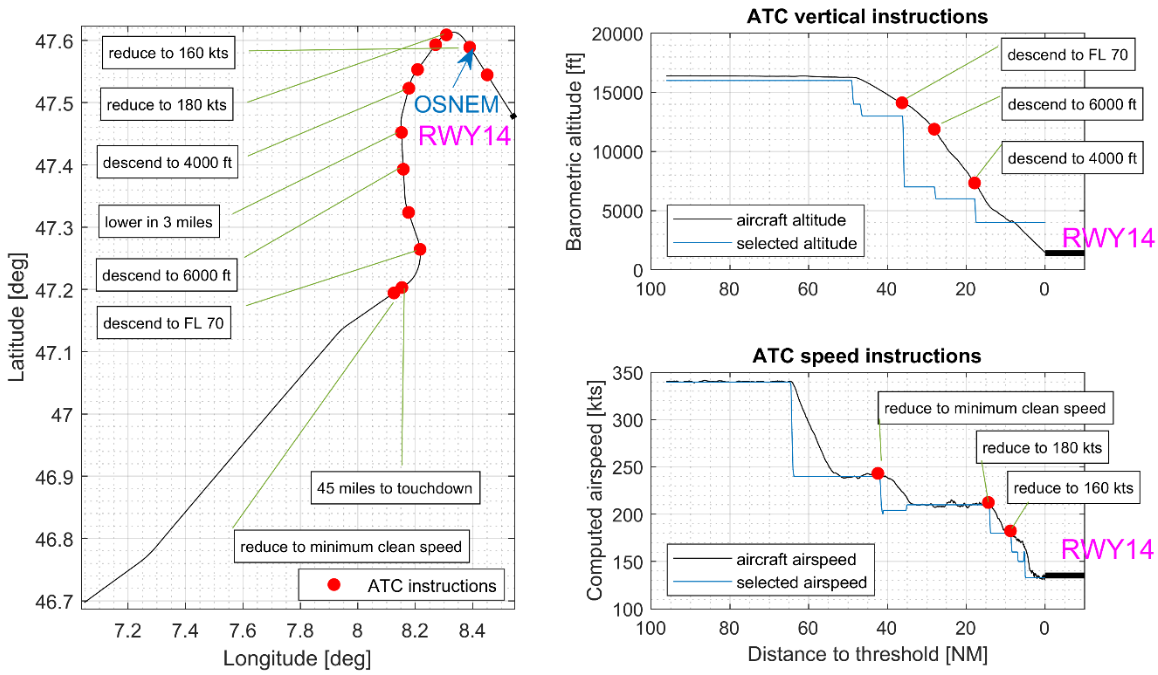

Figure 3 – Sample evaluation for flight #41 of 667, illustrating ATC instructions to the aircraft over lateral profile (left); vertical (upper right) and speed (lower right) instructions and the respective resulting profiles flown. OSNEM is the Final Approach Point (FAP) for runway 14.
Note: the wording of the instructions has been harmonised for analysis and may not be verbatim.

The first part of the analysis [4] was dedicated to a general overview of all investigated flights. It was identified that the investigated flights cover very different states related also to different parameters like mass, speed, altitude and position at the TMA. Even though all flights concern the same aircraft type approaching to land on the same runway, the respective developments of the approaches look very different. This includes the configuration setting, speed management, use of speed brakes, etc. and thus affects fuel burn and noise exposure. These differences are intensified by ATC instructions related to the vertical, lateral and speed profiles and the weather conditions. An average tailwind of 2-5 kts was determined from the meteorological measurements, and nearly 95% of the approaches used the Continuous Descent Approach (CDA) procedure. Another consistency was seen in the usage of high-lift devices and landing gear. The set points of Flaps 1 and Flaps 2 were bound to certain speeds but widely scattered along the distance to the runway. On the other side, the extension of the landing gear was bound to a certain distance but widely scattered along the speed. Finally, Flaps 3 and Flaps Full configurations had no big range regarding speed and distance [5].

[1] High-lift devices comprise flaps and slats, but as they are not independently operable on the Airbus A320, the four discrete settings for approach are operationally termed “Flaps 1”, “Flaps 2”, “Flaps 3” and “Flaps F (full)”.

Within this analysis two geographical points on the approach path were investigated in more detail: the FAP for runway 14 “OSNEM” and the 1000 ft gate above airfield level (AAL). At OSNEM it was clearly seen that two common speed restrictions are given by ATC at this part of the approach: 160 kts and 180 kts. For the 1000 ft gate AAL, the stabilisation was analysed based on the speed, thrust setting and the high-lift and landing gear configuration. Approximately 12% of the flights did not fulfil the stabilisation criteria.

After creating a general overview based on the investigated data, the flights were clustered along suitable criteria to discover effects on fuel burn and noise exposure. Even though DYNCAT includes all parties and effects in the TMA, special focus was on the impact of ATC instructions. Therefore, the data was separated by the different types of ATC instructions (vertical, lateral and speed). The impact of ATC speed restrictions was investigated in detail, because within this categorisation there is a small share of flights which do not have such restrictions, which made it possible to compare the flights with ATC speed instructions against those without. Furthermore, the flights which received ATC speed instructions were separated into subcategories to identify the impact of certain combinations of speed instructions on energy management during approach. The assessment of the different clusters showed that different ATC instructions lead to well comparable groups of flights with equivalent speed levels and similar approach profiles yet from a variety of flight paths and piloting strategies up to threshold. This allowed the quantification of the impact of the ATC instructions in fuel burn and also in noise exposure for each of the separate flight groups. The results showed that speed instructions, for instance minimum clean or less, especially when given early during the transition phase, lead to high fuel consumption, due to the long-time flight in low speed levels correlated to earlier usage of Flaps 1 and also Flaps 2 configurations. A mean difference of almost 50 kg in fuel burned is observed when comparing the flights with speed restrictions to those without [4]. On the other hand, speed restrictions provide a well-defined airspeed guidance for the pilots during transition and final approach, which leads to lower usage of speed brakes and also to lower speed levels for the landing gear extension. The less speed restrictions were given to the pilots by ATC, the higher was the usage of speed brakes during the final approach, and also the landing gear deployment was performed at higher speed levels, which ceteris paribus contributes significantly to the noise exposure and noise footprint. However, as the number of speed instructions generally is increased with traffic density, when the arrival trajectories are also generally longer, this may be an artefact and better pilot support in configuration management from the on-board systems could prevent the noise increase.

The evaluation of the lateral instructions revealed that there is less influence of the level of traffic on the ATC instructions than expected. The main differences could be seen for those arrival routes in which there is more margin in the airspace available and consequently there is a higher variety in the ATC lateral instructions. In summary, it could be confirmed that the design of the airspace in the surrounding of the airport is the main driver for the number and type of lateral instructions [4].

The detailed analysis of the vertical instructions revealed that different guidance strategies for the incoming flights are adopted, especially based on the arrival route. The most impacting factor leading to a higher fuel consumption is a precipitated instruction to descent to a lower flight level, which is not compatible with the aircraft’s optimal approach procedure. In most cases this leads to a shallower approach during the last track miles or even to level flight segments, requiring the application of extra thrust.

Furthermore, it could be identified that neither the actual wind conditions experienced by the aircraft nor the weather forecast have an influence on the ATC procedures and instructions. The impact of the presence of headwind components on increased fuel consumption could be clearly demonstrated and confirms the expected effects [4].

3. Potential for improvement

As presented above, large differences exist even between flights employing the same nominal procedures with identical initial conditions and comparable atmospheric states. For example, Flaps 1 and Flaps 2 settings are bound to certain structural limits for airspeeds but widely distributed over altitude and distance for the different flights. The distance with deviations up to 40 NM at which Flaps 1 and Flaps 2 are configured is still characterised by many different flight variations.

Also, it can be seen that 20% of the approaches have already extended the landing gear at about 7 NM from the runway threshold. Generally, at the time of landing gear extension the indicated airspeeds and altitudes are in the range of 130 kts to 230 kts and 2200 ft to 11000 ft, respectively. This is due to the fact that under certain circumstances, the pilots receive instructions from ATC which can only be realised with the Airbus A320 through early extension of the landing gear, increasing aerodynamic drag in order to reduce the excess of energy. Obviously, there is a huge potential to avoid unnecessary aircraft noise impact on the ground by shifting the extension of high-lift devices and landing gear closer to the runway with more appropriate procedures and optimised energy management.

However, within the complex framework of today's airspace structures and traffic density and especially in different boundary conditions (e.g. wind and aircraft mass), the implementation of an approach that is as fuel-efficient, low in CO_2 emissions and energy-optimised as possible (zero fuel waste) is a major challenge for the flight crew. Optimal on-board energy management requires precise flying of vertical approach profiles for which little guidance is available: the pilot has to decide, in compliance with ATC requirements, when to reduce speed, to set high-lift devices and to extend the landing gear in order to reach the approach speed at the stabilisation altitude. The earlier the configurations are initiated, the sooner the target approach speed will be achieved, so that additional thrust is needed. In fact, the use of speed brakes, unnecessary engine thrust and premature configuration changes over the optimal profile are the main causes of increased noise impact and fuel consumption as presented in [5]. If, on the other hand, the configurations are set too late, the aircraft may no longer be able to reduce the excess of kinetic energy, which would require to initiate a go-around. Since this means a considerable delay and significant extra costs, priority is always given by the flight crews to a stabilised approach over an energetically optimised one. Consequently, approaches tend to be carried out with additional reserves to the detriment of fuel consumption.

It should be noted at this point that this problem is not due to an inadequate qualification of pilots. On the contrary, the precise execution of the approach procedures is a great challenge, and even years of experience do not lead to optimal results. Each airport and each runway have their own characteristics (e.g. in Frankfurt, because of parallel runways, flights at the intermediate approach level are performed early and for a longer time, whereas in Zurich or London approaches from an energy excess situation are part of the daily routine). The avionics systems support even of the latest FMS developments for new aircraft designs includes only Flaps 1 and Flaps 2 extension points, which are statically computed along the vertical reference profile, based on the published transitions and very limited wind information; the full configuration sequence is not available. Once the pre-programmed transition routes of the FMS are left – and most arrivals are performed under radar vectoring – information about the expected lateral profile is no longer available and the FMS calculations are obsolete. The pilots' lack of information about the length of the lateral flight path and upcoming speed constraints (if any) can be identified as major cause of the problem to perform an optimised approach: Only with a lot of experience can a pilot anticipate these local conditions.

With a pilot assistance system providing an intuitive indication of the current energy status of the aircraft, taking into account the expected distance (e.g. dynamic transitions), time-over-target for the FAP, the wind information and an intuitive visualisation derived from this, a sustainable contribution could be made in the short term for more economical and ecological approaches. Such a system will be presented in this paper.

Further potential for improvement concerns the way ATC instructions are issued. Typically airspeed, altitude and heading instructions must be applied immediately by the flight crews. The lack of information for them regarding the exact time of the next altitude or airspeed instruction leads to unnecessary conservative approaches, which might already be mitigated by instruction tolerances where possible, especially with regard to the airspeed (e.g. "minimum 180 kts" instead of "reduce 180 kts") or the time of leaving an intermediate altitude (e.g. "when ready descent FL 70" instead of "descent FL 70"). This would not only allow to fly closer to the optimum aerodynamic conditions of the aircraft type at its current weight, but could help to avoid thrust-intensive short level segments until the next clearance is given. It was demonstrated in Zurich during a flight test campaign that a speed range at the FAP with a certain tolerance band (170 – 185 kts) allows a reduction in fuel consumption [1].

Finally, rapid changes in wind direction and/or speed can disturb energy management. For example, a sudden appearance of tailwind can cause the need for speed brakes deployment. Despite the fact that the current wind situation is observed by the preceding aircraft, this information is usually not shared with ATC or the following aircraft. Only the ground wind is communicated by ATC, which has no informational content about the vertical wind layer. A potential for improvement would be the implementation of a datalink to share wind information of preceding aircraft with the following aircraft directly or via ATC to make the approach more predictable to the pilots or aircraft systems. This solution could also provide further information about vertical winds (thermals), which influence possible sink rates, or the presence of icing conditions. The latter can also affect the energy management during approach by requiring higher minimum flying speeds; the use of anti-icing means increases engine idle speeds and results in a small loss of thrust. The timely transmission of information about the atmosphere to be flown through in the future thus is a prerequisite for the energy-optimised operation of the aircraft. However, the current state of FMS technology does not sufficiently fulfil this requirement. Although pilots can store atmospheric conditions such as wind and temperature at various flight level for the descent and approach phases in the FMS (up to 10 altitudes), this only provides a simplified representation of the environment. In addition, today's FMS do not make any or only very rudimentary dynamic adjustments to the flight plan based on the current flight condition, performing a blending between the observed wind and the wind predictions previously entered in the system. As a result, the predictions of the FMS optimisation algorithms tend to be conservative. Thus, the lack of precise and up-to-date information about the atmosphere to be flown through in the future, especially in the case of strong unpredictable deviations in approach / departure, represents a significant disadvantage of the current FMS generation.

4. The DYNCAT Operational Concept

Workshops were held and interviews conducted to better understand the current limitations and capabilities of pilots and air traffic controllers in their daily work, as well as their demands for future systems and concepts developed over short- or mid- to long-term. For example, it turned out that some display options are preferred (such as Primary Flight Display (PFD) and Navigation Display (ND)) and others preferably avoided (such as the Electronic Flight Bag (EFB)). Based on this, options were elaborated for the technical implementation of a pilot assistance system to be developed over the short term [6].

4.1 Concept Overview

The DYNCAT operational concept comprises changes to on-board and ground practices. The initial concept [6] is under refinement as a result of the performed simulation exercise described later.

4.1.1 Ground Practices

The goal of ATC is to establish and maintain separation between aircraft. To achieve maximum capacity at airports and therefore necessarily in approach, additionally, usually the separation between aircraft is reduced to the necessary minimum. As the separation is achieved by issuing suitable commands to individual aircraft, whose execution directly influences the aircraft’s behaviour and therefore noise and fuel efficiency, it is vital to understand the underlying factors influencing the issued commands. The controllers interviewed reported the way commands to achieve separation are selected as being mainly experience-driven, under consideration of several factors, e.g. weather, airspace structure and aircraft/pilot behaviour. The process was reported to not be pre-planned, but to take place in real-time.

Another aspect under investigation for its possible influence on approach planning by the pilots was the issuing of the remaining DTG from present aircraft position to landing by ATC to the pilots. According to the ATC experts, the DTG is given whenever practicable and, most importantly, if possible. However, the experts also reported that the DTG is usually only easily and accurately predictable for less dense traffic, and easiest for direct approaches. For pilots, however, it is more urgent to receive this information in dense traffic cases due to the less predictable and thus more difficult approach planning. Additionally, several limiting factors for ATC’s work have been mentioned, which comprised the weather situation, regulations for minimum separation, airspace structure, limited standardisation in aircraft procedures (e.g. between different companies) and traffic density [4][6].

The DYNCAT concept is not intended to impact the way the separation is established today by the Air Traffic Controllers (ATCos), with or without Arrival Manager (AMAN) systems, so that it will not affect the safety level of current operations. It is compliant with current vectoring methods (lateral instructions) that are applied to shorten or lengthen the aircraft trajectories. However, the concept foresees ATC providing to the cockpit the required information to compute a closed trajectory when the aircraft leaves its pre-planned route. This information can consist of a DTG or an Indicated Time of Arrival (ITA) [6] and should be updated if it changes. A reliable closed lateral path can be considered as an enabler and starting point for the on-board optimisation of the vertical profile. This would be enhanced by an uplink of information not available today like the vertical wind profile measured by a preceding approaching aircraft.

4.1.2 Airborne Practices

With the current, very limited support by the FMS, the pilots' preferred approach technique is the decelerated approach, which begins with an initial speed reduction to 250 kts, usually at FL 100 due to respective airspace regulations. The next speed reduction step is initiated mainly depending on the vertical profile, the associated wind and the aircraft weight. The favoured deceleration technique is in level flight, where, lacking systems support, the deceleration performance is easier to predict by the pilots than in descent, although this is in contradiction to the CDA concept.

The aim of the DYNCAT-assisted approach now is to facilitate the energy management on board, reducing noise, fuel consumption and the number of unstable approaches. The developed FMS algorithm extrapolates the current aircraft state in order to capture the active flight plan in the most likely way according to the operational context using information received from the ground (DTG or ITA). The result is the so-called Permanent Resume Trajectory (PRT) [7]: the horizontal flight path that acts as basis for the backward optimisation of configuration steps and vertical profile, taking into account the given constraints. The solution increases the situation awareness by providing certain cues to the pilots, in both lateral selected and managed modes, specifically the high-lift and landing gear sequences, but also a speed brakes request displayed only when absolutely necessary to reach eventual stabilisation. It is the aim to influence the descent scheme, timing and usage of aircraft configuration steps, and thus the noise level and fuel consumption, without affecting safety level. Considering particular characteristics of the aircraft automation (autopilot and autothrust) does further allow to avoid suboptimum flight conditions in terms of noise and fuel burn.

4.2 Components of the Concept Selected for Evaluation

For initial evaluation, a subset of the features of the operational concept has been implemented, with focus on the airborne side [8]. In order to be relevant in the cockpit, the energy management cues need to be based on information from ATC and reflect the controller's intent. Two different operating methods have been retained for the experimental evaluations, one based on DTG, the other based on the ITA information sharing. The most critical information for computation of an efficient vertical profile is the determination of the lateral trajectory consistent with the expected DTG / ITA and the expected geographical lateral path. This functionality will rely on the PRT mentioned above [7] that acts as an enabler for the DYNCAT feature.

Operationally, two situations can be distinguished (Figure 4). The first one (left plot) is obvious: when the aircraft flies in lateral managed mode, the relevant lateral trajectory is very well known. Indeed, it corresponds to the active flight plan (FPLN) along which the DYNCAT solution will improve the existing situation awareness to support the energy dissipation optimisation by displaying manual changes of vertical speed when required and extension of high-lift devices and landing gear. The colour coding of the associated pseudo-waypoints distinguishes between a smooth strategy (filled in black; optimum profile can be flown), an aggressive one (filled in green as depicted in middle and right plots; predicted energy dissipation is sufficient for a stabilised approach) and the situation where speed brakes are required to reach the target speeds at the respective pseudo-waypoints (filled in amber; not depicted).

The second operational situation (middle and right plots) is much more complex, but also much more common and not well addressed in the state of the art; it ensues with the onset of radar vectoring. The PRT concept foresees that initially, after reception of the first heading instruction, the PRT assumes to join the flight plan as soon as possible (middle plot), whereas after the later reception of the DTG the PRT is adjusted to conform with the remaining distance (right plot). The occurrence of vectoring increases with traffic density, in order to ensure the flights' separation and sequencing in dense airspace. As an example, according to the analysis of the current operations in Zurich (section 2 and [4]), a lateral instruction is issued to almost 97% of the flights, meaning that this use case cannot be neglected as it is today in the airborne systems.

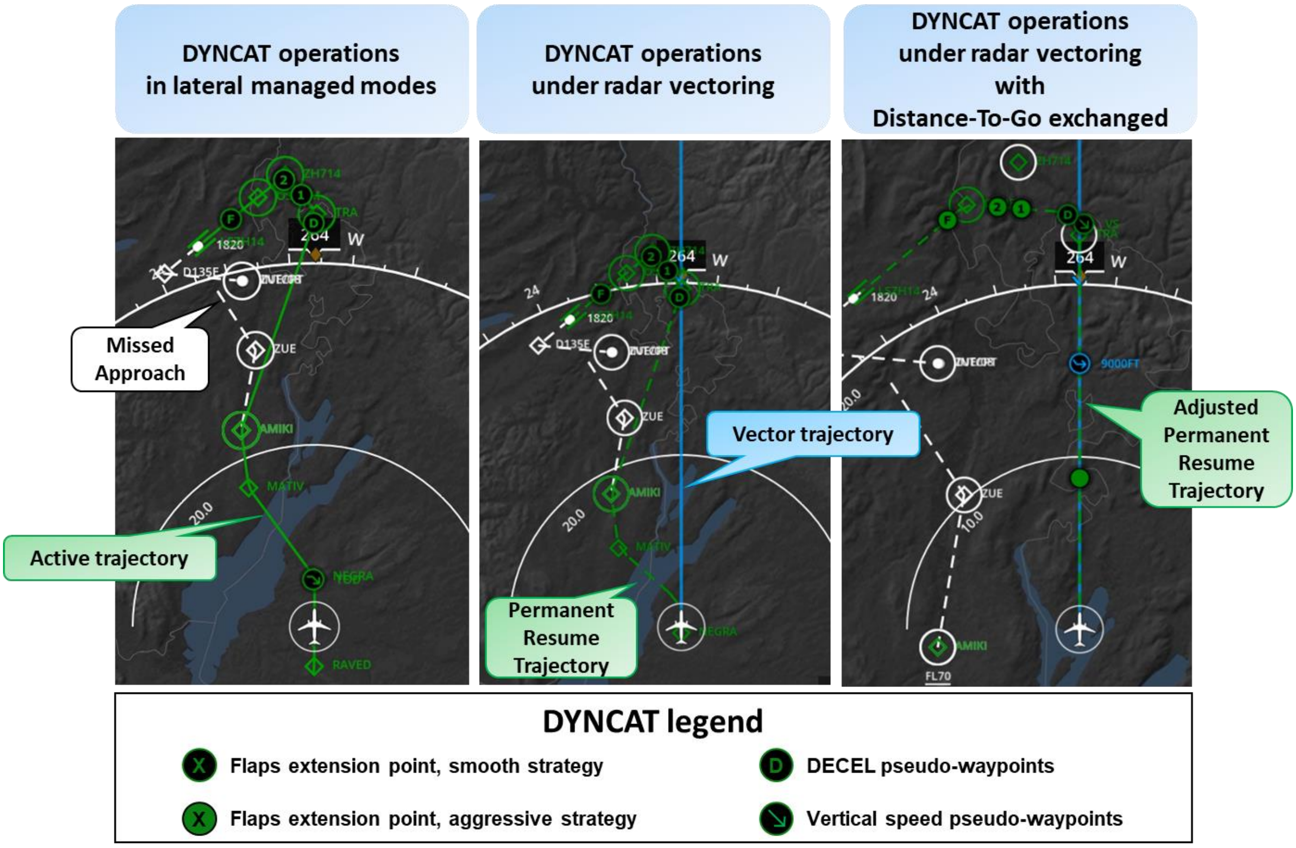

Figure 4 – DYNCAT flight plan depiction on Navigation Display in typical chronological order: initially managed mode displaying published transition (left); then selected mode employed under radar vectoring, before (middle) and after (right) reception of DTG information. The active trajectory or PRT, resp., are the reference for calculation of the pseudo waypoints for configuration and airspeed / vertical speed changes.

5. Experimental Implementation

The experimental implementation comprised several functional items of the selected components, namely FMS and CDS evolutions. The FMS functions were extended with dynamic pseudo-waypoints (cf. section 4.2 and Figure 4), optimised CDA vertical profile calculation, lateral path determination, next speed and altitude restrictions release points, improvements on the speed brakes messages and an optimised distance-to-land computation. The CDS evolutions included controller intent entry as well as strategic and tactical energy management cues including over-energy warnings [9]. The main objective was not to validate the way the information is presented in the cockpit, but to validate that all necessary information to fly an optimised descent and manage the energy efficiently is available.

Real-time simulator trials have been performed with pilots in the loop on an FMS test bench (Figure 5) employing typical Airbus controls, notably an A320 family Flight Control Unit (FCU), and an A321 aircraft simulation model. Due to the use of Instrument Flight Procedures, an external view was not provided. The CDS and FMS are experimental evolutions, with which the pilots were familiarised first. Actual flight scenarios from the operations data set (section 2) representing typical over-energy situations (Figure 6) were chosen as reference for the scenario design: a shortcut from “NEGRA” waypoint using vectoring with an initial continuation on present heading and a three-step vectored left turn onto the localiser. This scenario was flown by active airline crews, with and without the new support functions. All pilots held type ratings for the Airbus A320 family and/or other Airbus aircraft; all seniority levels from first officer to training captain were represented.

Figure 5 – Flight test simulation bench (Thales, Toulouse) with new generation Cockpit Display System (upper left, comprising ND and PFD) and A320 family Flight Control Unit (upper right)

All the validation means used to study the DYNCAT solution were defined with the objectives to assess the concept operational and technical feasibility, to conduct a preliminary performance assessment in terms of environment, human performance and safety, and to evaluate the flight predictability improvements thanks to the FMS trajectory stabilisation in selected modes [9]. The real-time pilot-in-the-loop simulation combined with the preliminary exercises involved an air traffic controller and twelve operational pilots that strongly contributed to increase the maturity of the solution and to refine the concept. Through questionnaires it was verified that they considered the scenarios, the simulation bench hardware and software (input devices, displays, accuracy of aircraft model, etc.) and the conduction of the experiment (briefing, ATC communication, crew resource management, etc.) respectively, sufficiently representative of the approach operations at Zurich airport, of the real aircraft and of real operations [10].

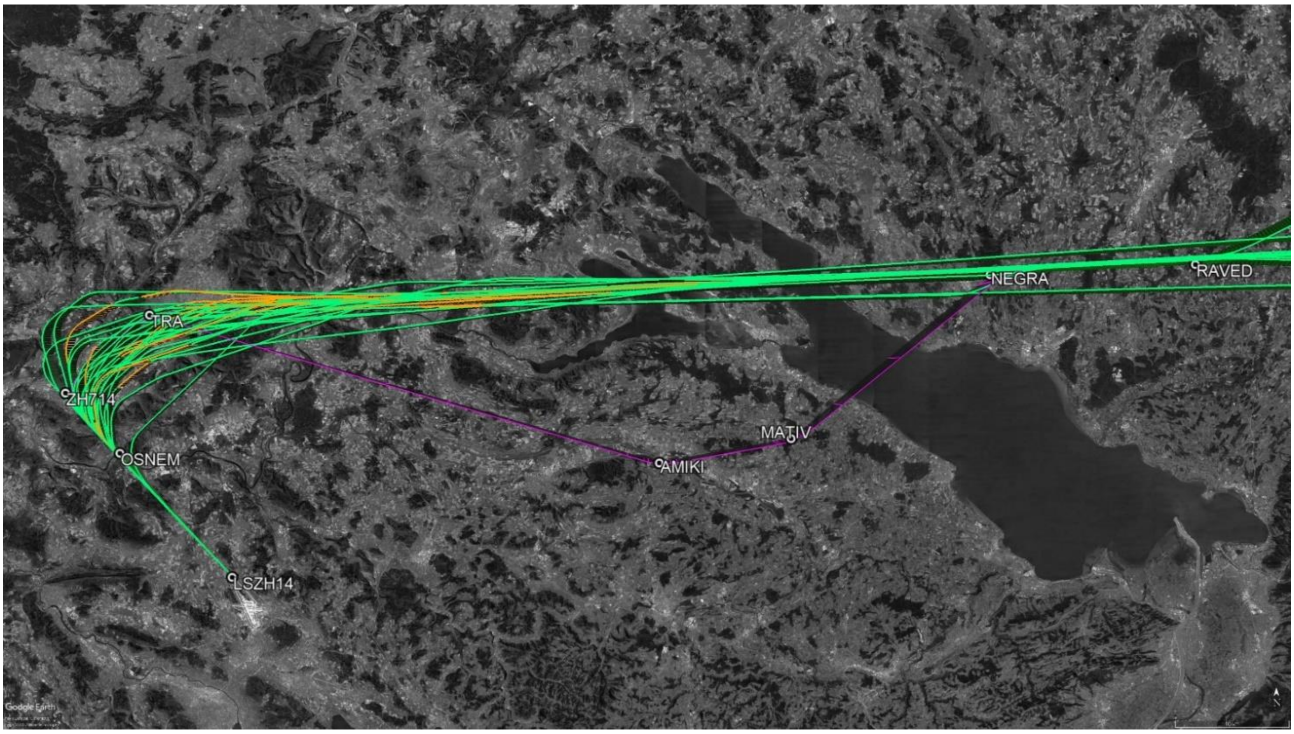

Figure 6 – Real flight trajectories selected as reference for piloted simulation scenarios. Those trajectories represent over-energy situations caused by a shortcut against the published transition (reference flight plan, depicted in purple) starting from NEGRA waypoint. OSNEM is the FAP, LZSH14 the runway threshold. (credit: Google Earth)

6. Concept Evaluation

The quantification of the potential for environmental impact (e.g. noise, CO_2 emission) reduction and for improvements through the novel pilot support function regarding flights predictability and flyability (including pilot workload and safety) is achieved through the comparison of the simulator runs flown with and without the new onboard functionalities. Besides the numerical evaluation of the technical parameters, the participating pilots' and ATCo's expert judgement was collected, for the former through debriefing questionnaires [10].

This validation phase confirmed that the solution is very well understood and appreciated by the pilots' community. They are confident that the DYNCAT function properly developed will help to achieve stable approaches, optimising energy management with improved situational awareness. All the actions proposed by the system to optimise the trajectory in selected mode were judged understandable and achievable, meaning that the proposed method is fully compliant with the actual airline's Standard Operating Procedures. The PRT computed by the FMS based on the ATCo intent is very well understood and considered as useful with all the necessary information to fly an optimised descent and manage the energy efficiently. The full set of energy management cues, composed of high-lift/landing gear pseudo-waypoints, speed brakes messages, vertical speed (V/S) pseudo-waypoint, permanent vertical deviation on the PFD speed scale as well as the optimum DTG and associated margin on the ND, was also evaluated. All the indications are stable enough and very helpful according to the pilots, even if some improvements have been identified that will be required for an industrialisation of the solution.

6.1 Operational Improvements

As far as possible with the limited number of simulator runs, the impact on stabilisation and predictability of approaches has been evaluated. These evaluations confirmed that the DYNCAT function is a good support to reduce spreads in altitude (Figure 7) and speed (Figure 8) profiles, increasing predictability of pilot actions and of the aircraft's position along the lateral profile. It enables the pilots to better handle the stabilisation for landing, supports the safety of the flight, and it helps to control the time with more accuracy. This last point might be particularly important in a context of a permanent growth of the air traffic. Indeed, more predictability would be helpful to maximise the throughput at the runway thresholds worldwide, by decreasing the safety buffers at ATC. This, in turn, would allow more reliable information on controller intent to be uplinked.

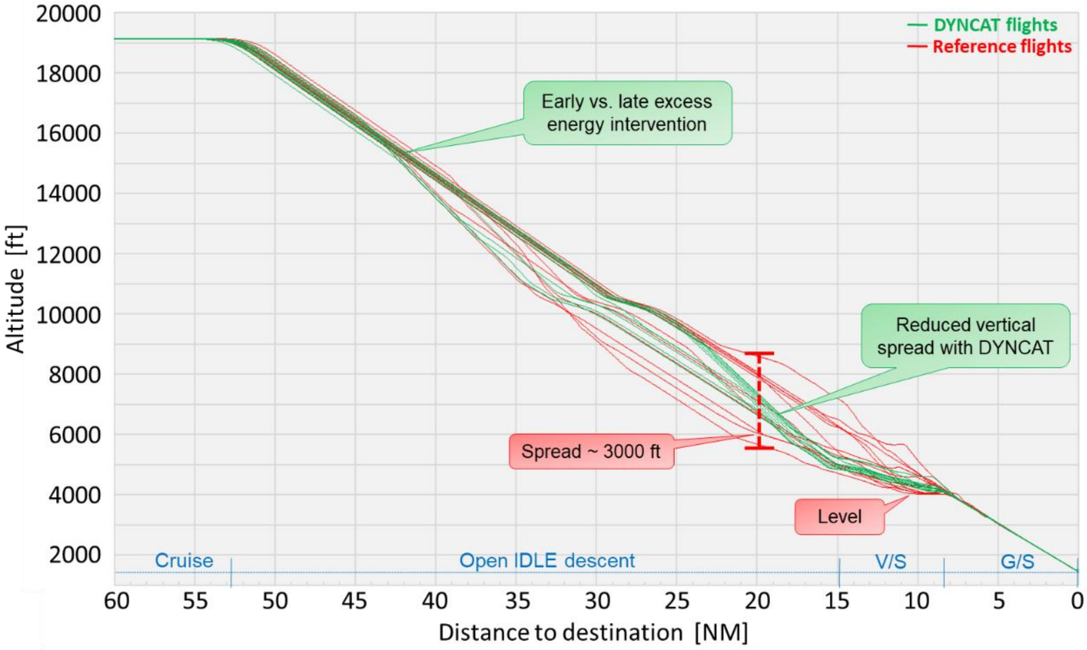

Figure 7 – Altitude profiles from piloted simulations, 12 without (reference, red) and 12 with the DYNCAT functionality (green). (V/S: vertical speed segment; GS: glideslope segment)

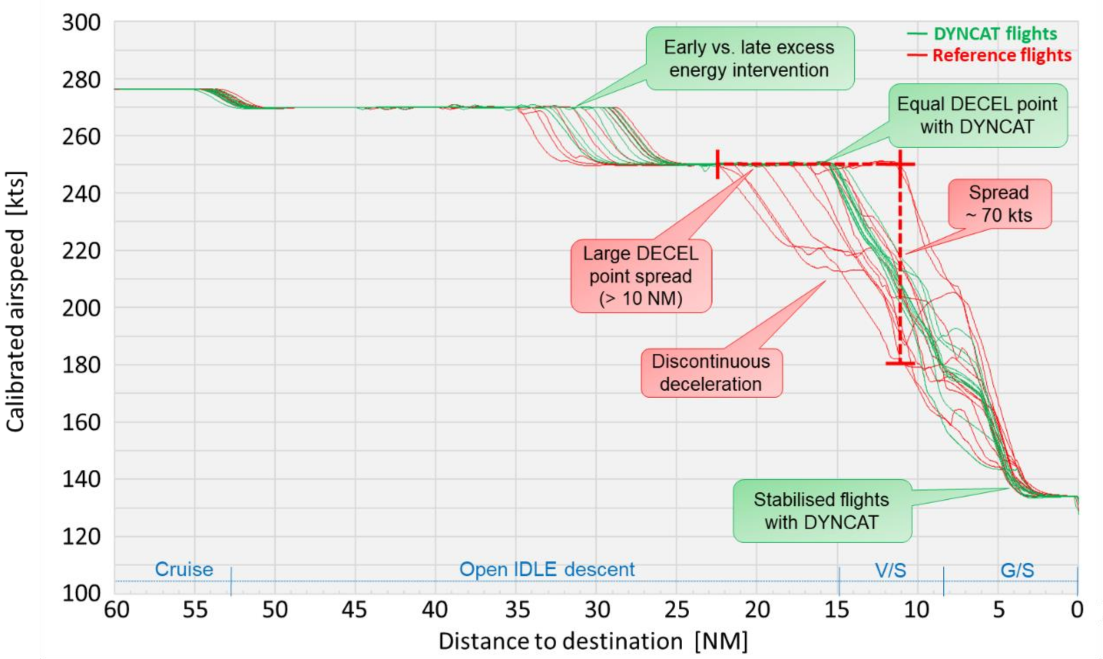

Figure 8 – Speed profiles from piloted simulations, 12 without (reference, red) and 12 with the DYNCAT functionality (green). (V/S: vertical speed segment; GS: glideslope segment)

6.2 Environmental Effects

This section quantifies the improvements obtained in the piloted real-time simulations with regard to fuel consumption / CO_2 generation and noise emission and exposure. While the former is determined from the simulated fuel flow, noise emission and propagation has been calculated with the high-fidelity spectral aircraft noise simulation tool *sonAIR*.

As shown in Figure 9, the implemented solution permits to the delay the approach idle thrust increase and to limit engine spool-up during the deceleration towards the approach speed. Indeed, thanks to continuous deceleration, the engines are much less strained with the DYNCAT function activated. The pilot feedback generally acknowledges that such a solution will help to save fuel and to reduce noise emissions.

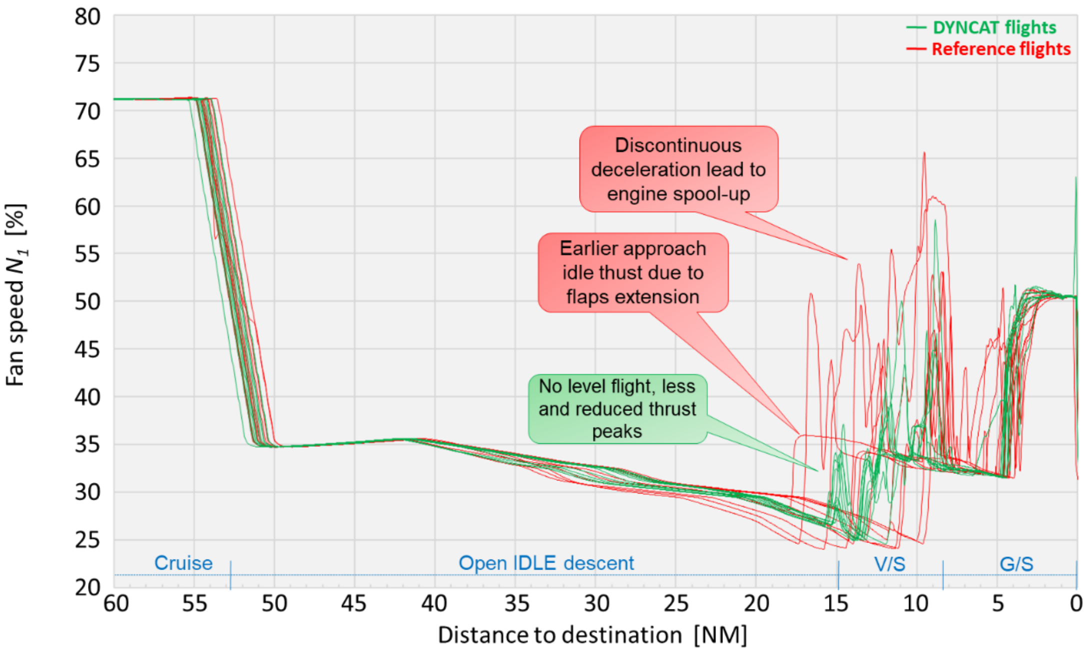

Figure 9 – Engine fan speed N_1 (expressed as percentage of maximum normal rotational speed, indicating thrust level) from piloted simulations, 12 without (reference, red) and 12 with the DYNCAT functionality (green). (V/S: vertical speed segment; GS: glideslope segment)

The latter are quantified with the noise simulation tool sonAIR [11][12][13] that is able to take into account the aircraft's configuration (high-lift devices and landing gears setting) and engine parameters and hence can demonstrate the effects of configuration changes in the noise footprint. The model was extended with a "moving receiver" which has a fixed distance and angle to the simulated aircraft to assess its noise emission along the flight trajectories independently of any receiver position on ground (cf. Figure 10 below), whose measured noise would also be influenced by any deviations in the trajectories. This further allows a sensitivity analysis of all flight parameters in terms of their impact on the aircraft's noise emission and shows the key parameters for potential noise reduction.

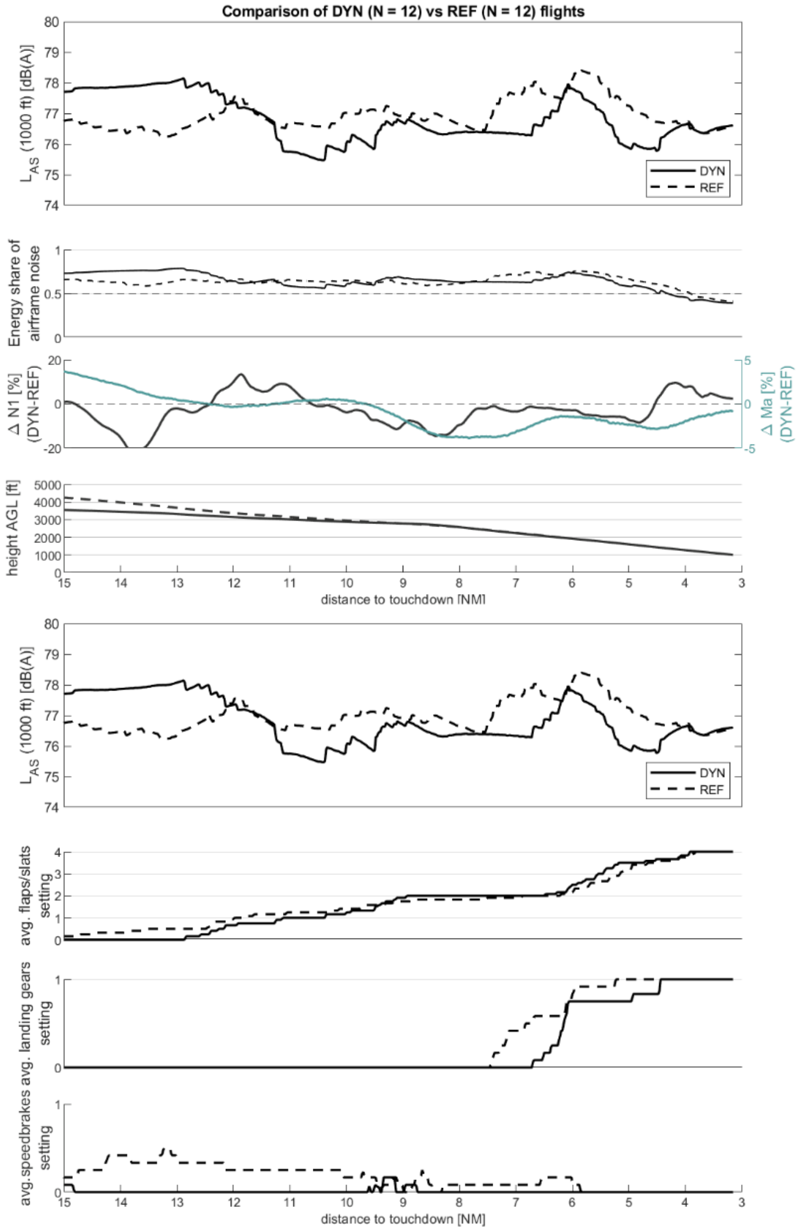

Figure 10 – Noise analysis and influencing parameters of 12 piloted simulation runs each with (solid lines) and without (dashed lines) DYNCAT function: (top) sound pressure level L_{AS}, obtained by simulations with a moving receiver, complemented with (from second to bottom): energy share of airframe noise against total noise; differences in engine fan speed *N1* and Mach number *Ma*; height above ground; averaged configuration for high-lift devices (discrete positions 0 (clean) to 4 (full)), landing gears (0 = up, 1 = extended) and speed brakes (0 = retracted, 0.5 = half and 1 = full extension).

Figure 10 shows the average sound radiated by the aircraft of 12 flights using the DYNCAT function (DYN) in comparison with 12 reference flights without it (REF), which was obtained by simulations with the moving receiver. The plots are described in more detail in the caption. Total noise emission consists of airframe noise and engine noise; it can be seen that almost over the entire approach, the energy share of the former predominates. Since the airspeed in particular, but also the configuration influence the airframe noise emission, these flight variables have the greatest impact on the total noise emission.

Thereby, flights with the DYNCAT function produce higher noise levels between 12 and 15 NM mainly due to higher speed. In contrast, the noise footprint of DYNCAT flights is smaller in the remaining part of flight, the latter being a consequence of an optimal use of high-lift devices and on average lower thrust settings. In the last flight segment, the influence of the later extension of the landing gears becomes clearly visible.

Figure 11 shows corresponding noise footprints on the ground, where all flight trajectories have been straightened for this specific evaluation. This was done to eliminate the lateral dispersion of the tracks which would strongly influence the noise exposure on ground, but is not an effect of the usage of the DYNCAT function. To make the simulations location-independent, flat and acoustically soft ground (grassland) was assumed. The map section here covers a distance of more than 30 NM to touchdown, in order to show further effects on noise influenced by use of the DYNCAT function. It must be mentioned though that legally relevant areas are only in the range of slightly above 80 dB L_{AE} (A-weighted sound exposure level).

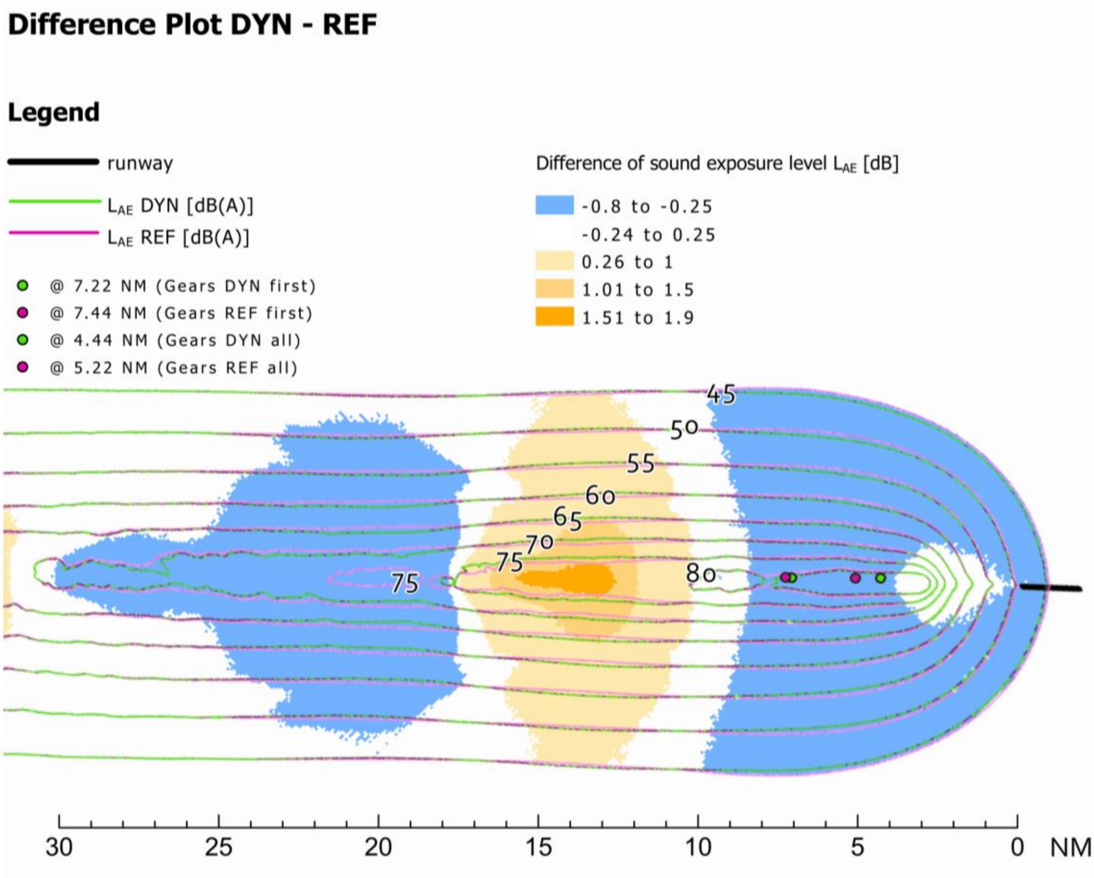

Figure 11 – Differential plots (DYNCAT and reference; colour coded blue and orange) and noise contours (green and purple, resp.) of calculated sound exposure level L_{AE} at the ground for straightened trajectories. The ground is assumed flat and acoustically soft (grassland). The filled circles denote the respective earliest and latest landing gear extension points.

At greater distances to touchdown (> 18 NM) it can be seen that the flights using the DYNCAT function are somewhat quieter, since the engine is mostly in idle compared to the reference flights. Furthermore, it can be observed that the L_{AE} difference decreases rapidly laterally to the flight path and that mainly areas below the flight path are affected. Around 15 NM before touchdown, an area with higher levels for flights using DYNCAT is visible. However, segments where the L_{AE} is around 80 dB and above, correspond to the area where the DYNCAT function yields a reduction of the noise exposure. This is explained by the earlier excess energy dissipation with the use of DYNCAT, resulting in a momentary increase in sound emission, and noise can consequently be reduced in later flight segments.

It must be noted, however, that the reference flights and therefore the comparison of results may contain a certain bias. All approaches started from a high-energy situation and specified the Point of Descent (PoD). The real-world data analysis (section 2 and [4]) of comparable situations strongly suggests that if the pilots could have freely chosen this PoD, the reference flights would also contain lower-level and therefore noisier approaches, increasing the relative noise benefits of the DYNCAT function.

7. Summary and Conclusions

Based on an analysis of the current practices, exemplarily for Airbus A320-214 approaches to runway 14 at Zurich airport, a concept was developed to decrease the negative impact of the current mismatch of ground and airborne procedures. The core of this concept, a novel pilot support function for energy and configuration management, was exemplarily implemented and evaluated in piloted real-time fixed-base simulation for an Airbus A321. The comparison of simulated flights with and without the new functionality allowed to quantify the potential for environmental impact (noise, CO_2 emission) reduction and measure improvements on flights' predictability and flyability (including pilot workload and safety).

For the investigated scenario, a typical over-energy situation, the DYNCAT concept yields a reduction of noise levels in the areas with highest exposition, which are relevant for legal compliance issues. Further away from the airport, there is a section where flights with DYNCAT showed slightly higher noise footprints. The latter is a consequence of higher travelling speeds, which, however, are beneficial to reduce fuel consumption. Hence, there is target conflict in that aspect: To fly as quietly as possible, speed has to be reduced before altitude in the energy management. In order to optimise fuel consumption, however, the opposite strategy would be best. DYNCAT allows to choose an ideal compromise between these contradictory requirements, namely that higher speed can be taken into account in regions where noise is not yet a major issue. It is expected that the noise benefits of the DYNCAT function are underestimated as a consequence of the experiment design and would be even higher if the pilots could have freely chosen the point of descent.

However, the expected fuel and noise benefits appeared to be very linked to the ATC data accuracy and way of working. This raises the need for strong involvement of an ATCo/AMAN in the loop to achieve the expected savings, but, as the evaluations also confirmed that the DYNCAT functionality is a good pilot support for more predictable altitude, speed and lateral profiles, this enables mutual benefits for ground and airborne sides. Better predictability of the individual flight, including better control of the time, would allow to decrease the safety buffers at ATC. This in turn would not only be beneficial for maximising the throughput at the runway thresholds worldwide, but also increase the reliability of controller intent information uplinked as basis for the on-board planning, thus closing the virtuous circle. Furthermore, the system enables the pilots to better handle the stabilisation for landing, thus supporting the safety of the flight.

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