



Improved configuration management for greener approaches: evaluation of a novel pilot support concept

Tobias Bauer¹ · Fethi Abdelmoula¹ · Johan Boyer² · Martin Gerber³ · Jonas Meister⁴ · Jean Marc Wunderli⁴

Received: 30 March 2023 / Revised: 20 February 2025 / Accepted: 24 April 2025
© The Author(s) 2025

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 optimally manage speed and configuration changes of the aircraft. Consequently, approach operations at busy airports are virtually always noisier and less fuel-efficient than technically possible. The DYN-CAT project combined all relevant data sources (on-board operational data, ATC commands, noise measurement data, surrounding traffic, and weather information) 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) and Cockpit Display System (CDS) capabilities. These features were evaluated regarding operational (pilots' workload and situational awareness) and environmental (fuel burn and noise exposure levels) improvements through piloted simulator trials on a fixed-based test bench. The present partial and initial implementation of the functions for the Airbus A320 family evaluates favourably with respect to the above criteria when compared with the state of the art, i.e., support by current FMS functions.

Keywords Aircraft energy management · Fuel saving · Noise abatement · Flaps and landing gear management · Pilot assistance system

List of symbols

Δ	Delta (Difference)
L_{AE}	A-weighted sound exposure level
L_{AS}	A-weighted sound pressure level with time constant SLOW (1 s)
N1	Engine fan speed (expressed as percentage of maximum normal rotational speed)

Abbreviations

AAL	Above airfield level
AGL	Above ground level
AMAN	Arrival manager
ATC	Air traffic control
ATCo	Air traffic controller
ATM	Air traffic management
CDA	Continuous descent approach
CDO	Continuous descent operation
CDS	Cockpit display system
COVID	Corona virus disease
CTA	Controlled time of arrival
dB	Decibel
DTG	Distance to go
DYN	DYN-CAT
DYN-CAT	Dynamic configuration adjustment in the TMA
EFB	Electronic flight bag
FAP	Final approach point
FCOM	Flight crew operating manual

✉ Tobias Bauer
tobias.bauer@dlr.de

¹ Institute of Flight Systems, DLR e.V. (German Aerospace Center), Braunschweig, Germany

² Thales AVS France SAS, Toulouse, France

³ Swiss Skylab Foundation, Dübendorf, Switzerland

⁴ Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland

FCU	Flight control unit
FMS	Flight management system
GIS	Geographic information system
GS	Ground speed
ITA	Indicated time of arrival
LDLP	Low-drag low-power
MCDU	Multipurpose control and display unit
ND	Navigation display
NM	Nautical miles
PFD	Primary flight display
PoD	Point of Descent
PRT	Permanent resume trajectory
REF	Reference
RNAV	Area navigation
RTA	Required time of arrival
RTS	Real time simulation
RWY	Runway
SOP	Standard operating procedure
STAR	Standard terminal arrival route
TBO	Trajectory-based operation
TMA	Terminal manoeuvring area
ToD	Top of descent
VLS	Lowest selectable speed
V/S	Vertical speed

1 Introduction

Even if exhibiting several dents in the growth curve due to occurrences like the financial crisis of 2008 or the COVID-19 pandemic in 2021/2022, the level of air traffic has been steadily growing over the longer term and is expected to continue to do so in the foreseeable future [1]. The reduction of its environmental impact is therefore a necessity. This concerns not only the climate impact (comprising both CO₂ emission and non-CO₂ effects and addressed, e.g., by the European Commission [2, 3]) but also local air quality and noise exposure of the population especially in the vicinity of airports [4]. The widespread use of sustainable aviation fuels and the introduction of electrically powered aircraft types will ultimately decrease the climate impact, but the noise situation is not expected to be significantly enhanced by these measures except for the take-off and climb with electrically powered aircraft [5]. Hence, procedural solutions reducing fuel burn and noise exposure cannot only offer faster remedy than the replacement of aircraft fleets but will retain their value when these changes have taken place. We therefore address the optimisation of flight operations in environmental regard, focussing on noise and fuel burn and on descent and approach in the Terminal Manoeuvring Area (TMA).

1.1 Motivation

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 (minimising flight times and 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 and extension of the landing gear) with associated changes in airspeed. The former are manually commanded and both highly specific, depending not only on the type of aircraft, but also on its current weight and the weather situation along the flight path (primarily wind, but also temperature and static air pressure). The management of configuration and the speed regime are dependent on each other, while today's systems support for it is very limited. Current state of the art of airborne noise abatement is the Continuous Descent Operations (CDO) concept [6] that aims to minimise fuel consumption and engine noise by flying from the top of descent (ToD) down to the final approach at near idle power [7]; ideally, the use of airbrakes is avoided. 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. Furthermore, while idling minimises fuel flow, the production of further pollutants such as CO and HC is exponentially increased at low idle thrust [4]. These affect the local air quality if emitted at low altitudes. As this study mainly addresses descent and approach above the stabilisation altitude, however, only CO₂ and noise impact are investigated.

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 to increase drag and hence the deceleration potential of the aircraft. This does not only accelerate structural fatigue but unnecessarily increases maintenance costs, noise, thrust, fuel consumption, and generation of CO₂ and other pollutants [8].

Current FMS offer very limited support for fulfilling the requirements and recommendations in the FCOM outside the nominal case, which is statically calculated based on the published approach procedure and a few values for wind speed and direction over altitude. Hence, in the real world, in the presence of live ATC (altitude/speed/lateral) instructions to control the flight path and with the actual wind situation, this reference becomes obsolete and the optimisation of the configuration sequence depends on the pilots' experience, skills, and their access to the necessary information.

1.2 Previous work

Aircraft noise is not only a nuisance to many, but a serious health problem to affected people (causing sleep disturbance and increased risks for cardiovascular and metabolic diseases [9, 10]), so extensive research has been conducted since decades. Particular focus has been on the aircraft design side, namely on reducing the noise generated by the airframe and the propulsion system (cf., e.g., [11] for an overview). Not only will the current fleet need decades to be replaced with quieter types, but also the expected introduction of electric propulsion will have much more noise benefits for the take-off phase due to removal of the combustion system noise, while in approach, where the airframe noise often predominates for modern aircraft [12], the higher landing weight of electric a/c may even negatively affect noise levels [5].

Procedural solutions for noise abatement, i.e., the design of favourable approach paths on the ATM side and the optimisation of speed and configuration schedules in the on-board standard operating procedures (SOPs), have therefore been developed and are in widespread use today. Solutions comprise a redesign of routings to areas with lower noise sensitivity, increase of glideslope angles in the final approach segment [13], generally steeper and/or segmented approaches [14], and on-board procedures like the low-drag low-power (LDLP) approach (see [15] or [16] for a comparison of concepts).

The Continuous Descent Approach (CDA), meanwhile evolved into the CDO, concept has been studied extensively in the last decades both at the analytical/conceptual level (e.g., [17]) and in airport specific implementations (e.g.,

[18, 19]). In its ideal implementation, descent and approach are performed with engines in idle from the top of descent in cruise until the interception of the final approach path, typically the glideslope of the Instrument Landing System (ILS). The use of speed brakes is avoided as it is both a source of aerodynamic noise and an inefficiency in that it dissipates energy that has been introduced earlier at the cost of fuel burn. As the aircraft's energy is constantly decreasing, it is not possible to maintain both altitude and airspeed; consequently, level flight, which is a typical component of conventional approach procedures, can only be maintained for a short time.

In practice, each individual flight needs to perform the procedure differently, depending on the weather situation along the flight path (primarily wind, but also temperature and static air pressure), the type of aircraft, and on its current weight [7, 20]. Furthermore, while the differences between aircraft types are obviously much larger than between individual units of the same type, the latter—stemming from tolerances and aging of the engines and airframe [21]—are not negligible to an extent that would allow a fixed generic optimisation for the type. In the current system, the result is a significant decrease of the vertical and temporal predictability of incoming traffic flows, increasing Air Traffic Controllers' (ATCos) workload and requiring larger separation buffers, which in turn leads to airspace and runway capacity losses [20]. In major TMAs, these are usually not acceptable during peak hours, which significantly limits the viability of the concept.

Research to improve the situation has been conducted in various areas. On the ATM side, Rodríguez-Díaz et al. [22] considered a bi-objective model, namely addressing noise and fuel consumption/delays, in optimising the traffic sequencing, use of arrival routes, and choice of target runway at a multi-runway airport (Adolfo Suárez Madrid-Barajas Airport). The model works with average noise and fuel consumption data per aircraft type and tries to assign the faster routings to aircraft having higher fuel consumption, while distributing louder types over less noise sensitive routings. The Standard Terminal Arrival Routes (STARs) are assumed to be followed. This is a complementary approach to the DYNCAT concept which optimises the individual aircraft's execution of the instructed trajectory.

Sáez et al. [20] developed a four-dimensional (4D) trajectory negotiation/synchronisation process between the ATCo and the aircraft to manage arrival traffic in terminal airspace. This process takes place in the pre-sequencing area, while the aircraft are still en route, and generates dynamic arrival routes adapting to the current traffic demand. The aim of the optimisation is to allow the aircraft to fly neutral CDOs while ensuring separation throughout the procedure. A required time of arrival (RTA) assignment is found to allow to efficiently schedule traffic. The concept of operations

would ultimately remove the necessity of vectoring except for unforeseen or contingency situations, allowing the FMS to optimise the flight path under environmental goals. The DYNCAT approach addresses both the current operation of widespread vectoring and a possible future scenario of trajectory-based operations (TBOs), where still the aircraft's performance under actual circumstances needs to be taken into account.

The airborne side has been studied by de Jong et al. [23] and Prats et al. [24] who developed and investigated the TEMO (time and energy managed operations) concept that aims to optimise CDOs, while fulfilling with a very high accuracy controlled time of arrival (CTA) constraints at different metering fixes. The feasibility was demonstrated not only in batch simulations [23] but also in full-motion flight simulation and using a Cessna Citation II experimental aircraft. While managing the aircraft's energy state, the main focus was on the time control rather than the environmental impact (even if this a collateral benefit of proper energy management). The need for further work identified included the interception of and guidance on the final approach segment. Prats et al. [24] contains an extensive set of references on the development of the approach.

2 The DYNCAT Approach

The SESAR Exploratory Research project DYNCAT (“Dynamic Configuration Adjustment in the TMA”) [25] was conducted to improve the support of environmentally friendly flight execution. While the concept comprises data exchange between air and ground to accommodate the necessary individuality of trajectories without detrimental effects on capacity, the first step reported here consists in the development of an on-board system that supports pilots to optimally fly a given trajectory. It goes beyond the existing approaches by addressing the vectoring case—the vast majority of operations at major airports—where path and speed schedule are not known beforehand but reaction to ATC instructions is necessary, and by taking into account the necessity for stabilisation, an important safety goal, and a major driver for the conservatism observed in many approaches [7]. The approach considers both fuel/CO₂ and noise, which are generally detrimental goals, and provides continuously updated guidance based on real-time data and aircraft performance under actual circumstances. Finally, an important feature is the integration into the existing on-board guidance infrastructure (FMS and CDS).

The project started with a critical analysis of the current operations [26], a summary of which is available in [27]. Initial results of the development and assessment activities were presented at two conferences [28, 29] and the overall

approach summarised in an earlier conference paper [30], which the present one updates with the final findings.

The first part of this paper presents the analysis and concept development: In the following Sect. 3, a short overview of the analysis of the current operations is given as motivation for the development. The potential for improvement is analysed in Sect. 4. Section 5 describes the DYNCAT overall 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.

In the second part of the paper, we describe the experimental setup and results of the assessment of the core of DYNCAT's operational concept, a new FMS and CDS functionality supporting the flight crew in energy and configuration management during descent and approach in the TMA. The functionality is implemented in a test bench (as described in Sect. 6) and evaluated in piloted simulations regarding operational and environmental improvements (Sect. 7). The evaluation quantifies which improvements in CO₂ reduction and noise footprint could be possible with short-term (mainly on-board procedures) and mid-term (mainly new on-board system functionalities) measures.

3 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 and 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 [26, 27]. 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 databases. The flight paths depicted in Figs. 1 and 2 show the wide

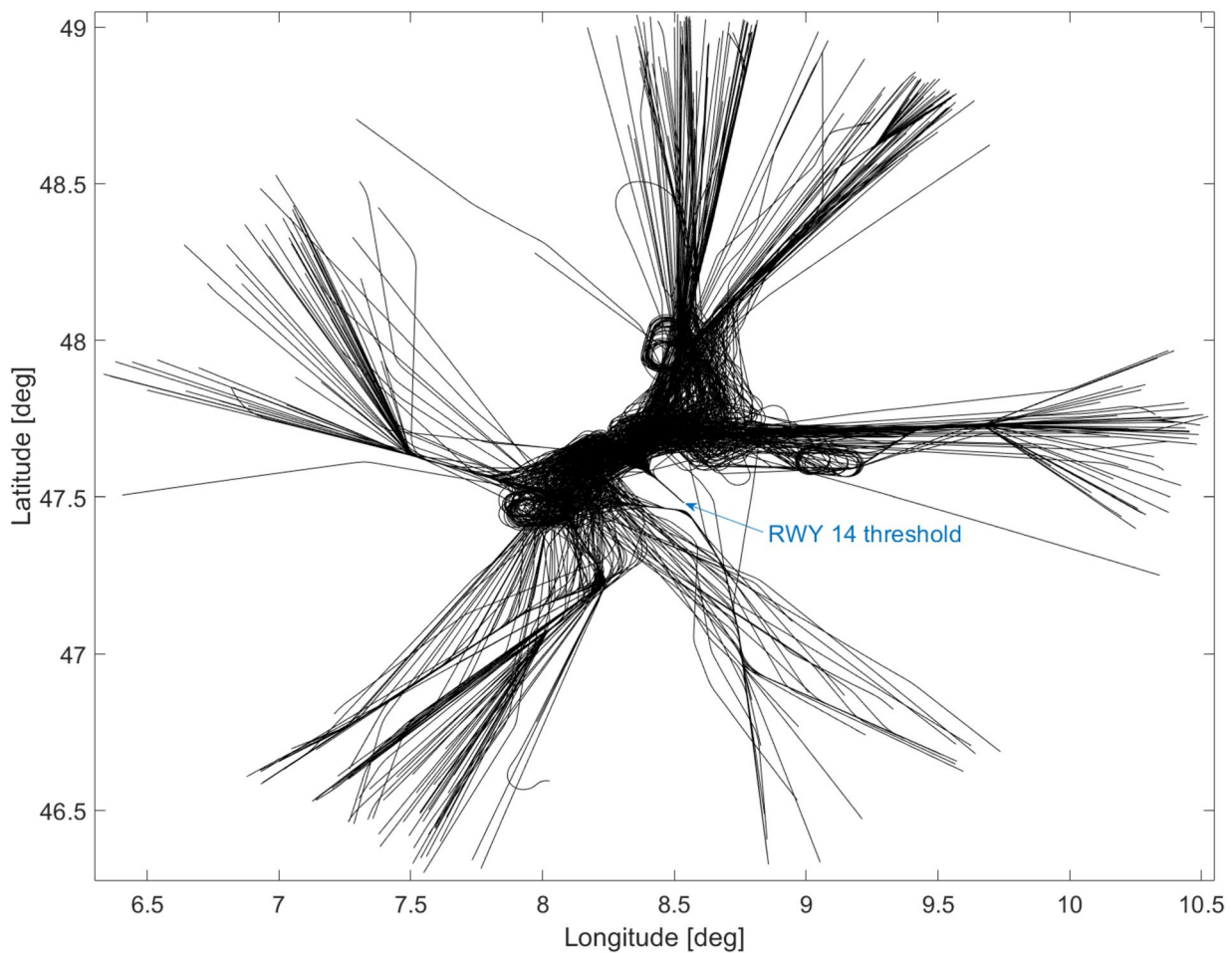


Fig. 1 Lateral flight paths (top view of ground tracks) of all 667 Airbus A320 flights into Zurich airport investigated for the analysis. The depicted tracks begin at Flight Level (FL) 100 and end at the threshold of the target runway 14, which can be seen in the centre of the figure

variety in executed horizontal and vertical profiles. The on-board 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 [27] 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).

In Fig. 3, 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 are 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 4 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

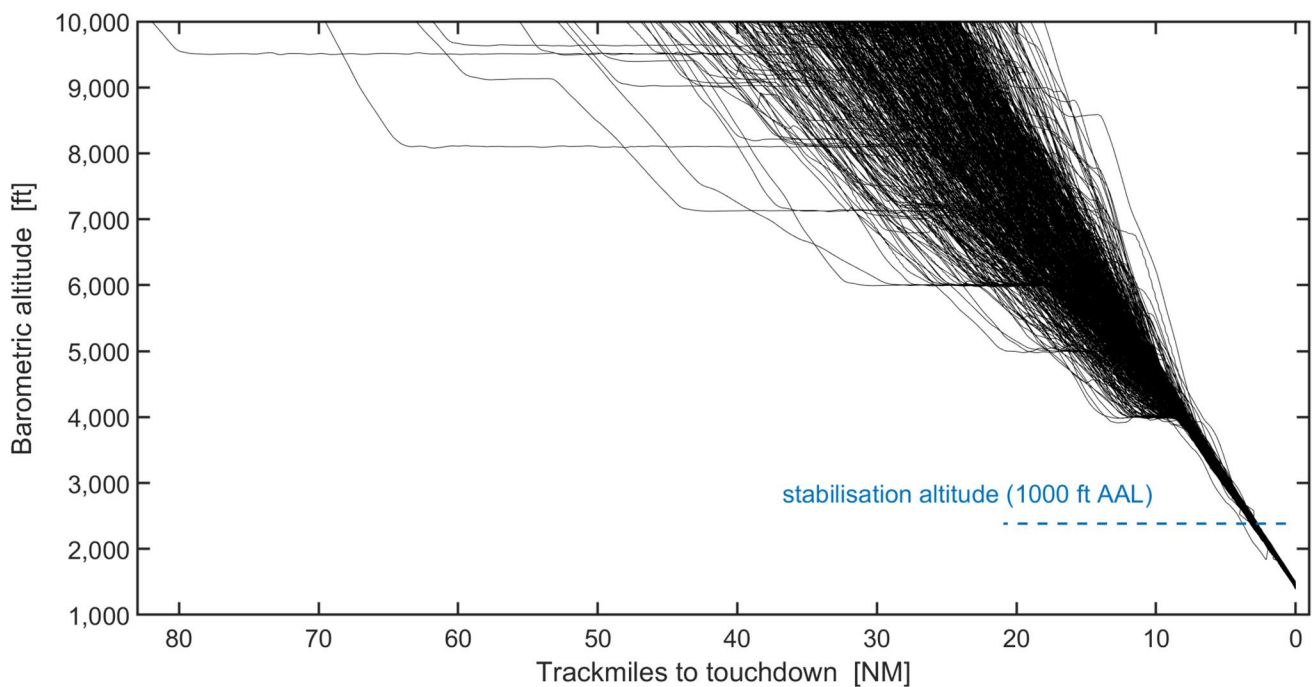


Fig. 2 Vertical flight profiles (developed over ground tracks as seen in Fig. 1) of flights investigated for the analysis. The depicted profiles begin at 10,000 ft altitude and end at the threshold of the target runway 14

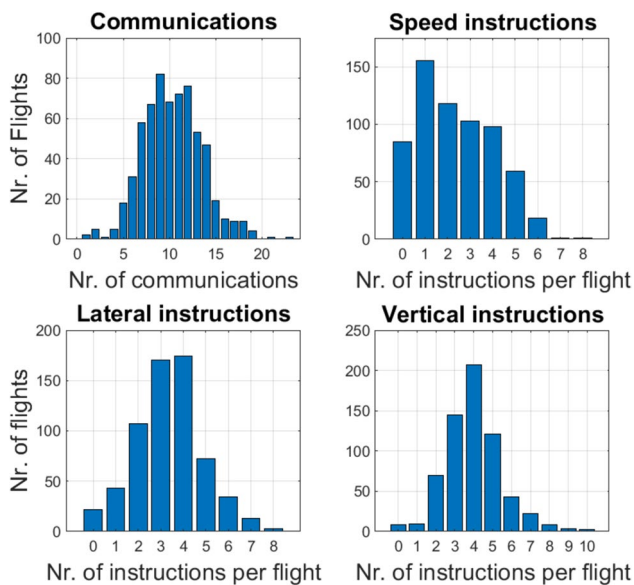


Fig. 3 Distribution of number of received radio calls per flight from the arrival controller: all received communications (upper left); communications related to speed (upper right); communications related to the lateral flight profile (lower left); communications related to the vertical flight profile (lower right) [27]

limited when the aircraft is flying close to the minimum clean speed. However, to comply with the descent instructions, the deployment of speed brakes is necessary. As a consequence, the pilots have to extend Flaps 1¹ 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.

The first part of the analysis [26] 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

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)”.

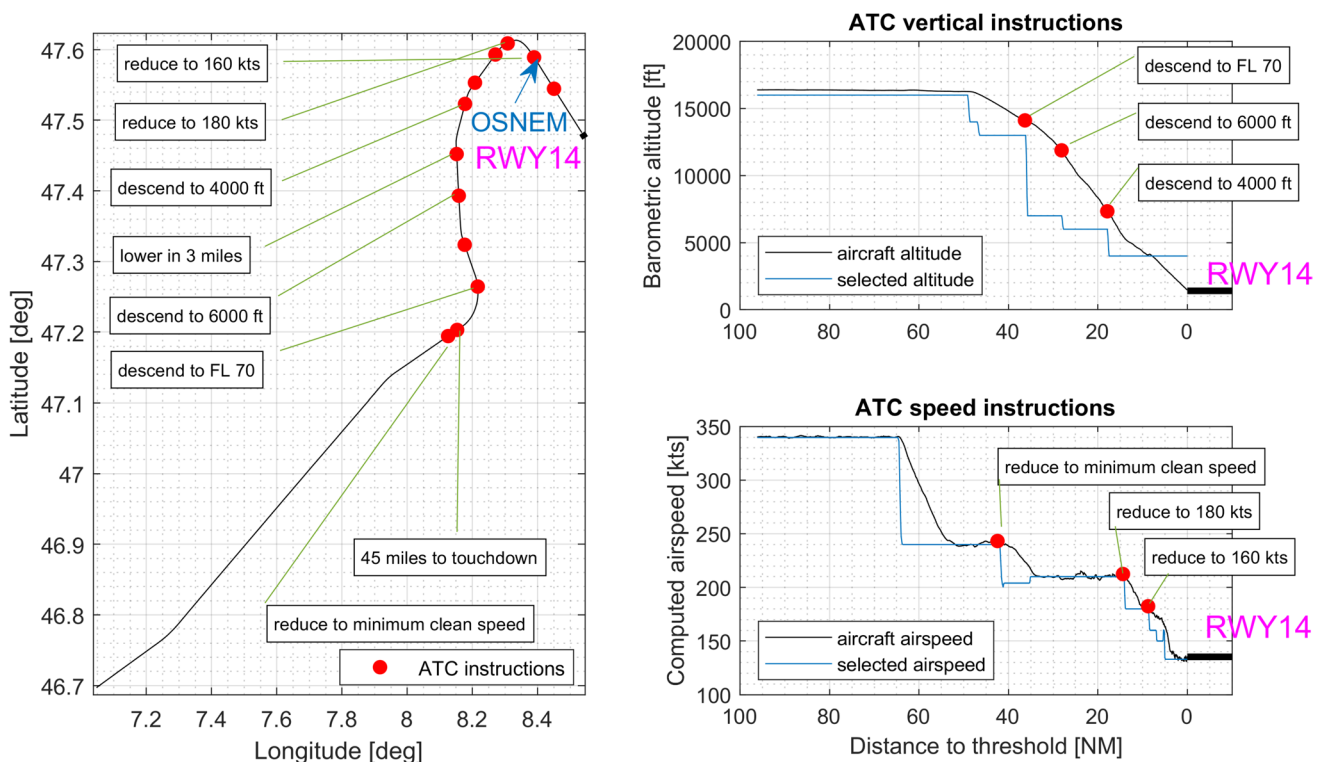


Fig. 4 Sample evaluation for flight #41 of 667, illustrating ATC instructions to the aircraft over lateral profile (left); vertical (upper right) and speed (lower right) instructions and the respective resulting

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

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 [27].

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 DYNCAIT includes all parties and effects in the TMA, special focus was on the impact of ATC instructions. Therefore, the data were 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 [26]. 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 [26].

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 [26].

4 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 11,000 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 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 CO₂ 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 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 [27]. 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 [7].

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.

5 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 [31].

5.1 Concept overview

The DYNCAT operational concept comprises changes to on-board and ground practices. The initial concept has been refinement as a result of the performed simulation exercise described later; the final one is available in [31].

5.1.1 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 [26, 31].

The DYNCAT concept is not intended to impact the way the separation is established today by the 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) [31] 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.

5.1.2 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 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) [32]: 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. Figure 5 shows a schematic overview of the concept for selected flight mode, as used in the experiments described here. The system also supports flight in managed mode, where the FMS directly controls speed and flight path.

5.2 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 [33]. To be relevant in the cockpit, the energy management cues [28] 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 and 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 [32] that acts as an enabler for the DYNCAT feature.

Operationally, two situations can be distinguished (Fig. 6). 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 [28] 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

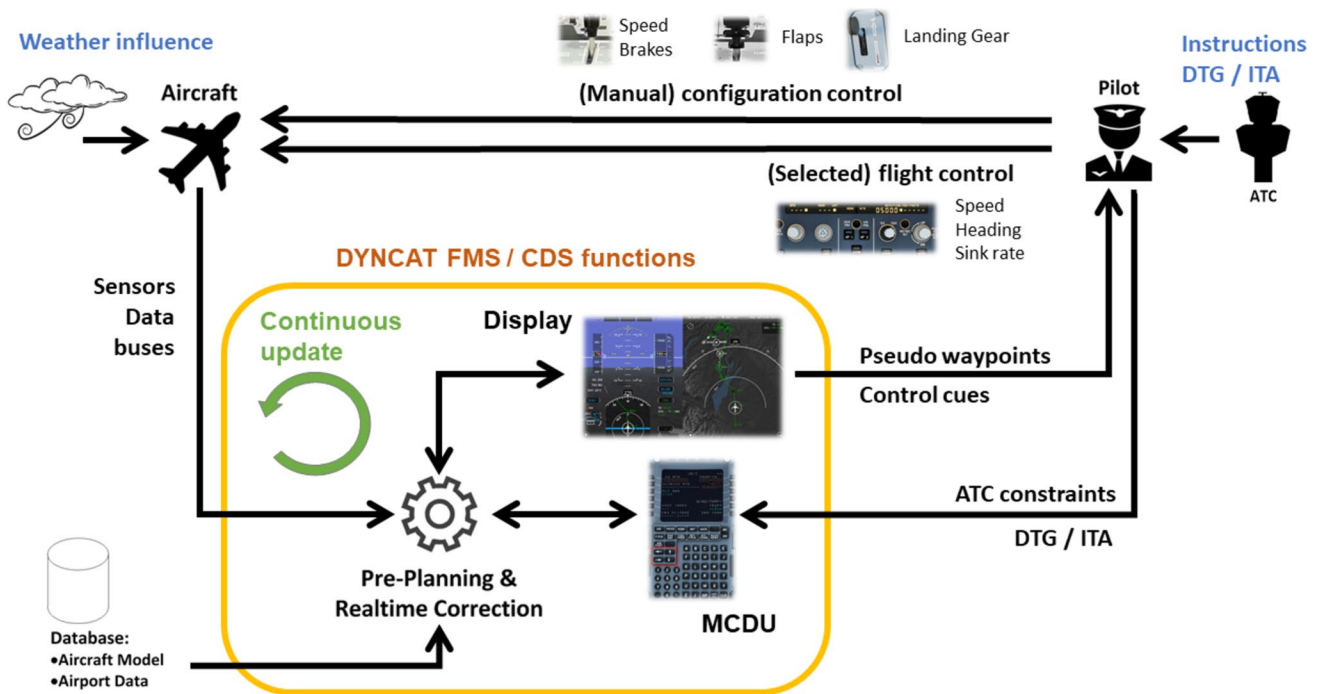


Fig. 5 Overview of approach for DYN-CAT pilot assistance in initial implementation as experimented. Based on instructions and information from ATC that are entered into the Multipurpose Control and

Display Unit (MCDU), the system provides cues to the pilots for optimal inputs to the flight control system and control of the configuration (which is always manual)

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 (Sect. 3 and [26]), 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.

6 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. Sect. 5.2 and Fig. 6), 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 [28, 29]. 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 [34].

Real-time simulator trials have been performed with pilots in the loop on an FMS test bench (Fig. 7) 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 (Sect. 3) representing typical over-energy situations (Fig. 8) 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.

All the validation means used to study the DYN-CAT solution were defined with the objectives to assess the concept operational and technical feasibility, to conduct a preliminary performance assessment in terms of

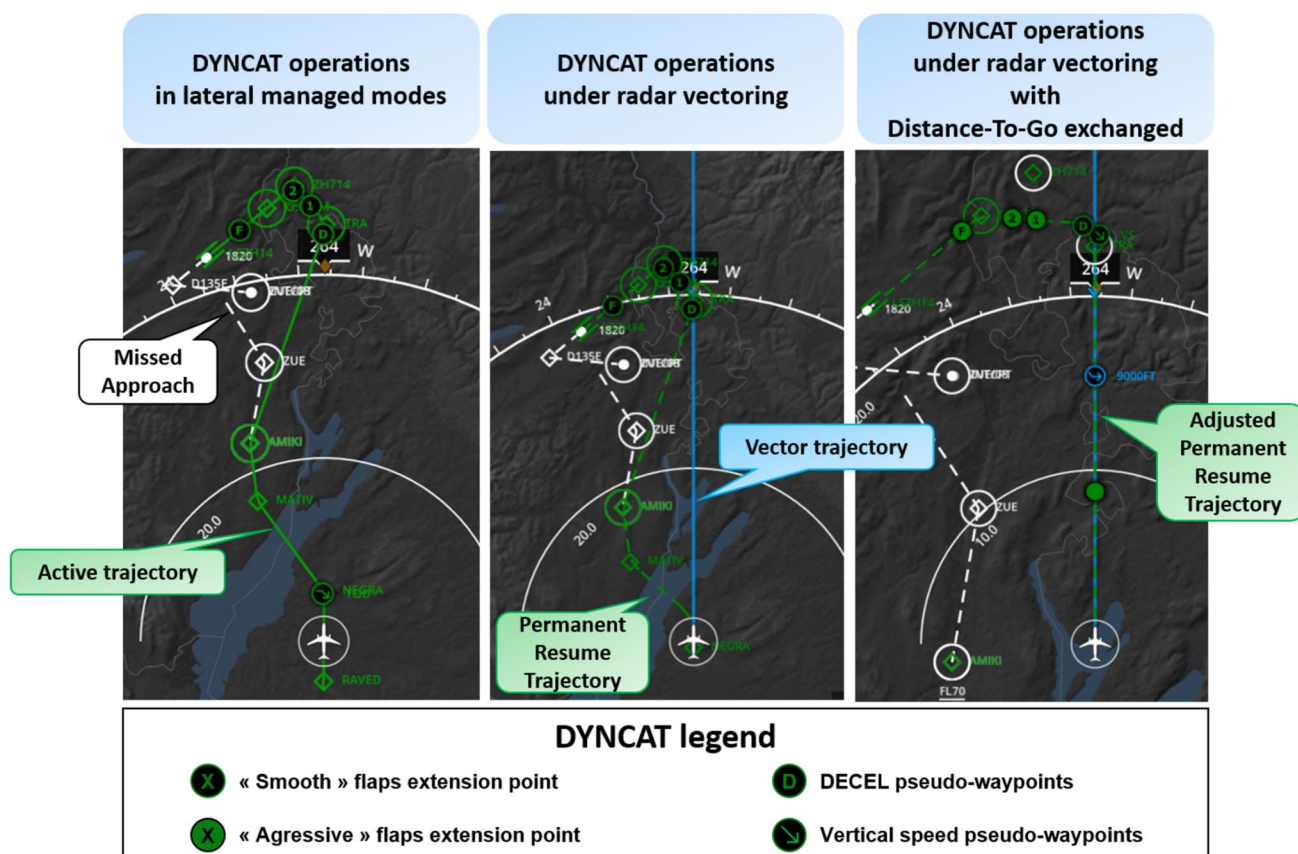


Fig. 6 DYNCAT flight plan depiction on Navigation Display in typical chronological order: initially managed mode displaying published transition (left); then selected mode employed under radar vectoring, before (middle) and after (right) reception of DTG information. The

active trajectory or PRT, resp., are the reference for calculation of the pseudo-waypoints for configuration and airspeed/vertical speed changes



Fig. 7 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)

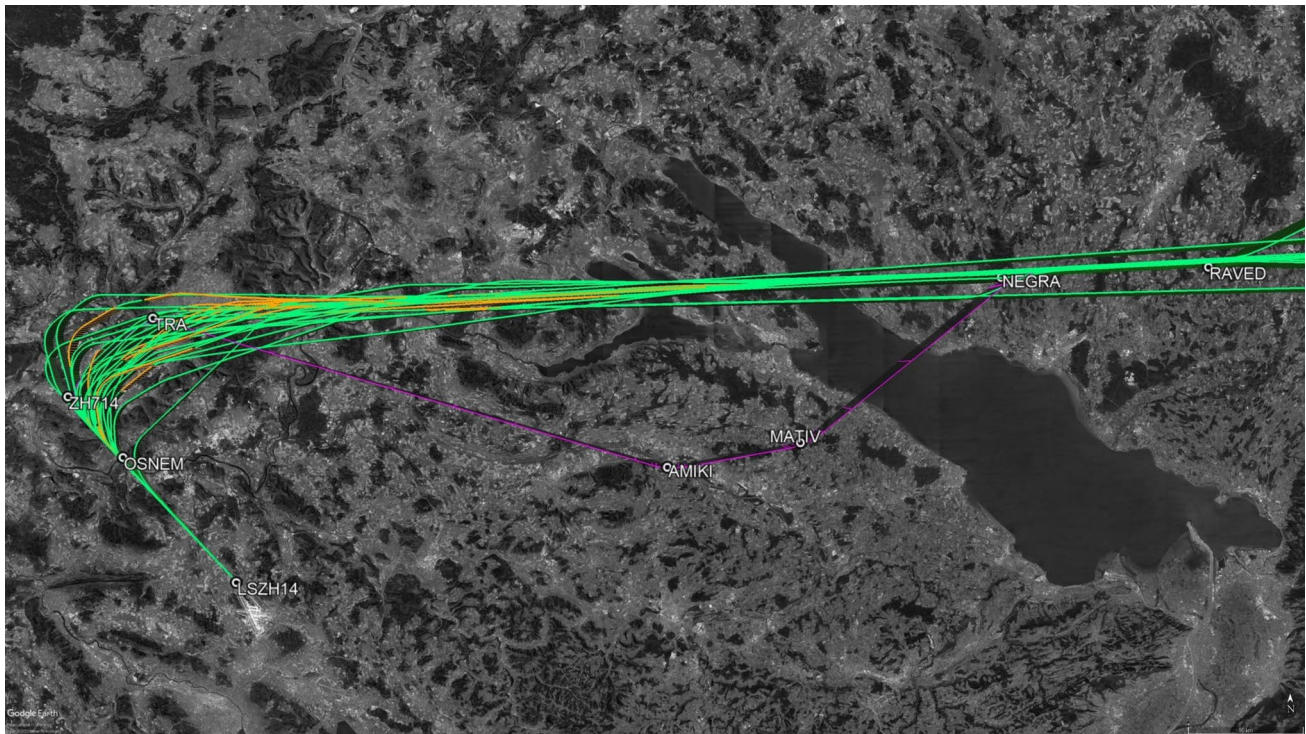


Fig. 8 Real flight trajectories selected as reference for piloted simulation scenarios. Those trajectories represent over-energy situations caused by a shortcut against the published transition (reference flight

plan, depicted in purple) starting from NEGRA waypoint. OSNEM is the FAP, LZSH14 the runway threshold (credit: Google Earth)

environment, human performance, and safety, and to evaluate the flight predictability improvements thanks to the FMS trajectory stabilisation in selected modes [34]. The real-time pilot-in-the-loop simulation combined with the preliminary exercises involved an air traffic controller and 12 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 [29, 35].

7 Concept evaluation

The quantification of the potential for environmental impact (i.e., noise and CO₂ 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

on-board functionalities. Fuel use and noise emissions were calculated from engineering models for aircraft and engine performance. Even if the CDS is an improved design not yet found in service at the time of the experiments, the (limited) supporting functions for flight plan and state prediction and the (lack of) cues for configuration management represent the state of the art in operational aircraft of the A320 family. Besides the numerical evaluation of the technical parameters, the participating pilots' and ATCo's expert judgement was collected, for the former through debriefing questionnaires [35].

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 [29, 33].

7.1 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 DYN-CAT function is a good support to reduce spreads in altitude (Fig. 9) and speed (Fig. 10) 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.

7.2 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 assuming 3.15 kg CO_2 produced per 1 kg fuel burnt [36], noise emission and propagation has been calculated with the high-fidelity spectral aircraft noise simulation tool sonAIR.

As shown in Fig. 11, the implemented solution permits to 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 DYN-CAT function activated. On average, flights using DYN-CAT saved 5.2 kg of fuel corresponding to approximately 16.4 kg of CO_2 emission reduction. This is a relatively small effect but needs to be seen in the context of tens of thousands approaches per year for this specific aircraft type to Zurich airport alone; moreover, the investigated scenario was an over-energy situation where no substantial savings could be expected in the first place. Also, the reference may be biased due to very good skills of the pilots involved (including above-average technical background and familiarity with the airport) and the fact that a simulation environment is not as stressful as the real operations. Still, the fuel use reflects the improved flight predictability

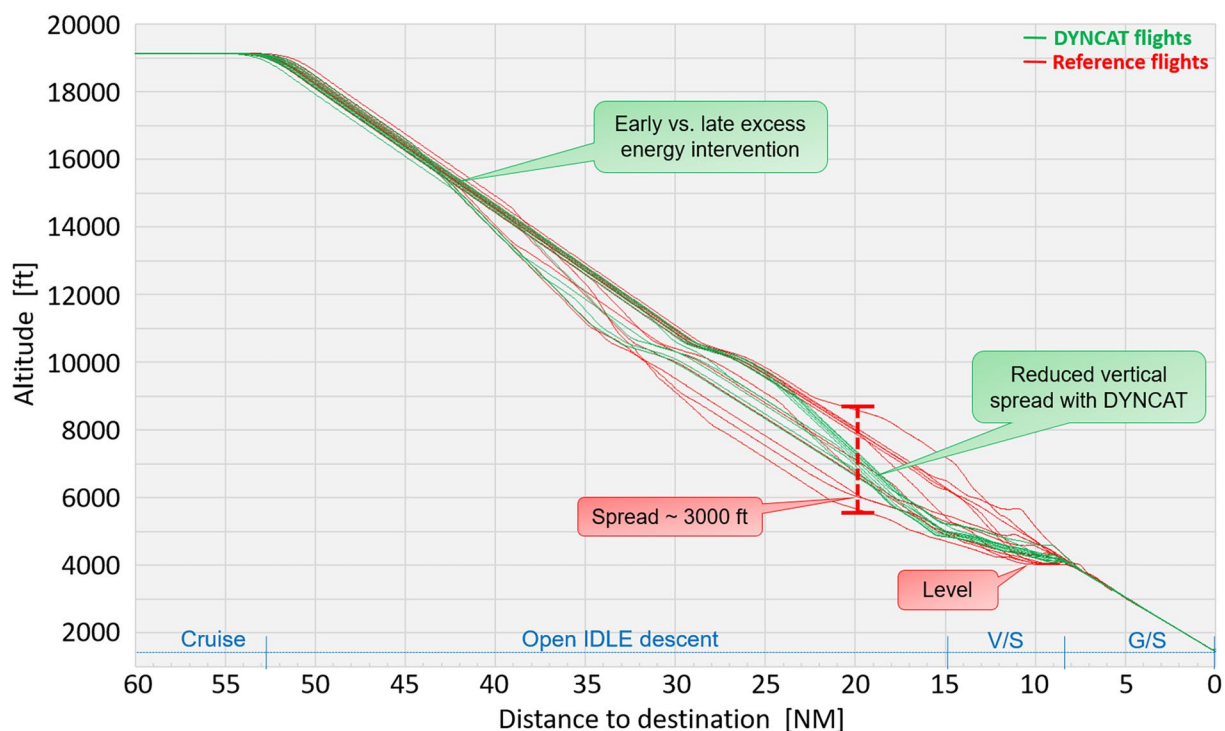


Fig. 9 Altitude profiles from piloted simulations, 12 without (reference, red) and 12 with the DYN-CAT functionality (green) (V/S: vertical speed segment; GS: glideslope segment)

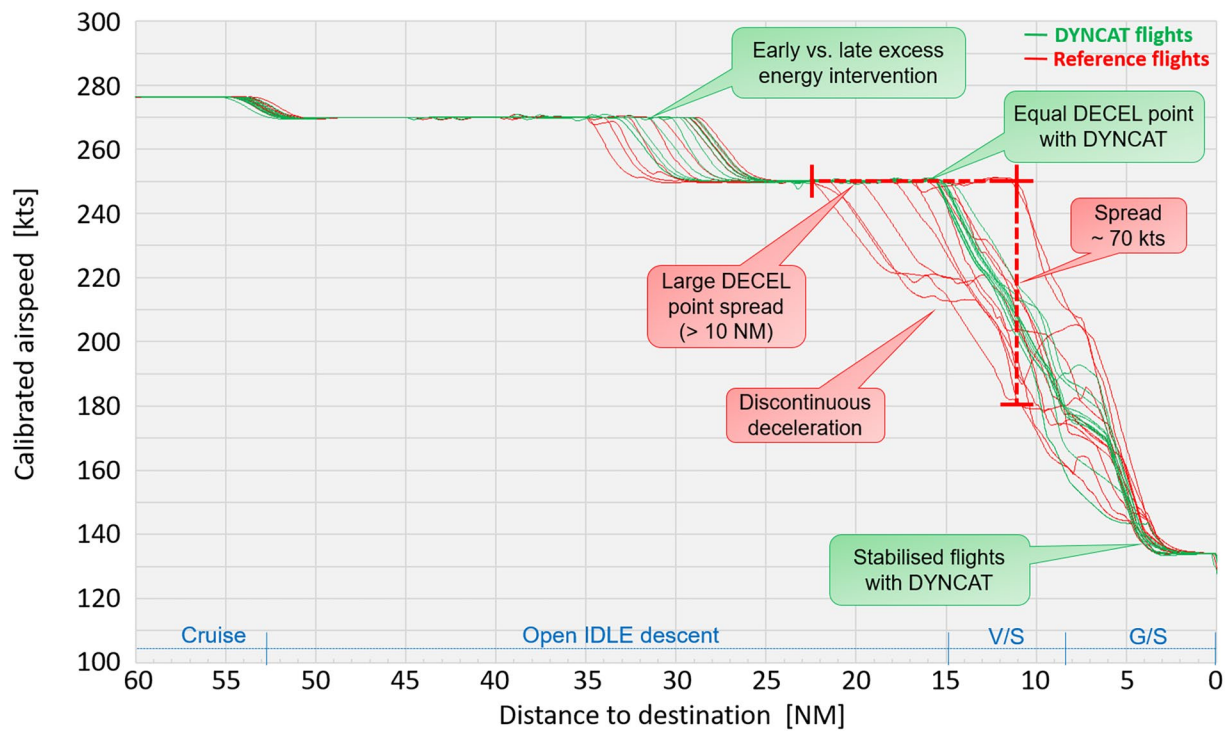


Fig. 10 Speed profiles from piloted simulations, 12 without (reference, red) and 12 with the DYNCAT functionality (green) (V/S: vertical speed segment; GS: glideslope segment)

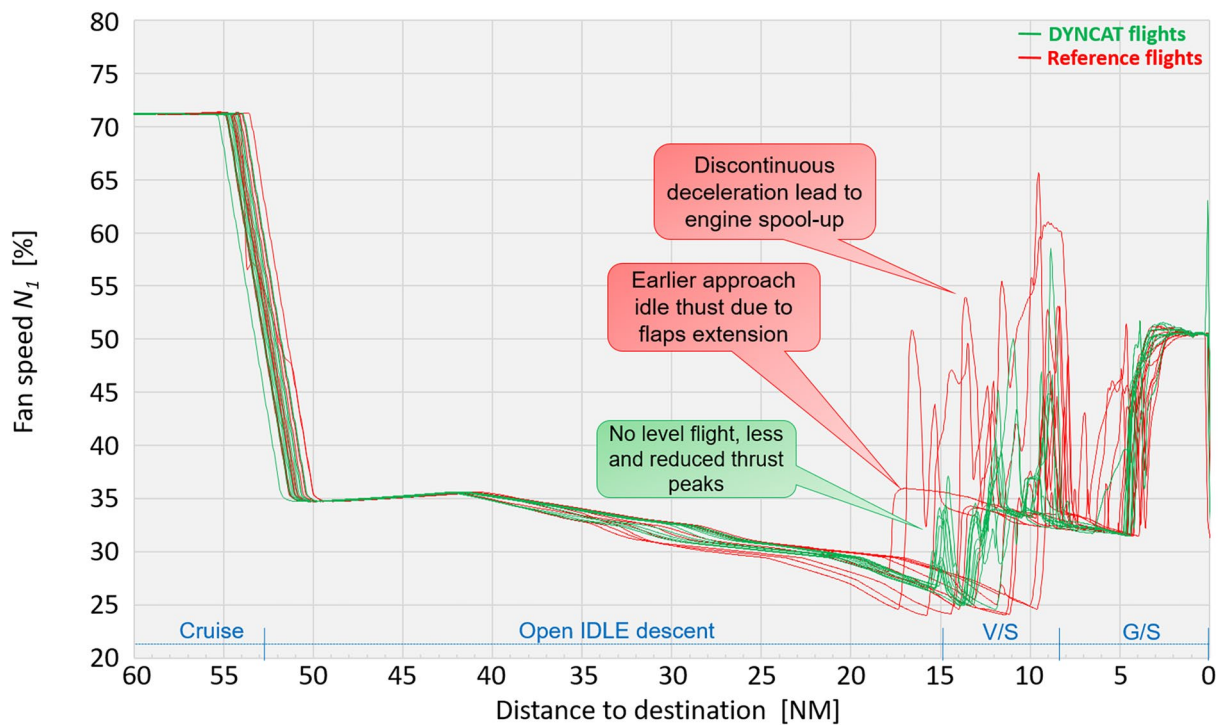


Fig. 11 Engine fan speed N_1 (expressed as percentage of maximum normal rotational speed, indicating thrust level) from piloted simulations, 12 without (reference, red) and 12 with the DYNCAT functionality (green) (V/S: vertical speed segment; GS: glideslope segment)

through the new FMS function: for the reference flights, the spread is substantially larger, with a standard deviation of 19.4 kg, compared to 4.6 kg for DYN-CAT. The reference cases yielded a range of fuel consumption from 252.3 kg to 320.5 kg with an average of 273 kg, with the best DYN-CAT approach at 243 kg. These values illustrate an environmental potential of 11% fuel reduction for this scenario that could be obtained by generalising the best practices [37].

The noise impact has been quantified with the noise simulation tool sonAIR [12, 38–40] 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 12), 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 12 shows the average sound radiated by the aircraft of 12 flights using the DYN-CAT 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. (Note that the height above airfield level does not affect the sound pressure levels shown in Fig. 12, but is relevant for the exposure on the ground, which is introduced in Fig. 13.)

Thereby, flights with the DYN-CAT function produce higher noise levels between 12 and 15 NM distance to threshold mainly due to higher speed. In this area, the system has specified a higher airspeed to reduce fuel consumption by spending less time, as the fuel flow in idle is not negligible. In contrast, the noise footprint of DYN-CAT 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 positive influence of the later extension of the landing gears becomes clearly visible.

Figure 13 shows corresponding noise footprints on the ground, where topography and ground cover have been obtained from Geographic Information System (GIS) data. The map section here covers a distance of more than 30 NM to touchdown to show further effects on noise influenced by

use of the DYN-CAT 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, cf. 80 dB contour line in Fig. 13).

At greater distances to touchdown (> 18 NM), it can be seen that the flights using the DYN-CAT 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 with perceptible sound reductions (the scattered dark blue areas are a consequence of terrain shielding following the lower flight altitude of the DYN-CAT flights, but are of little practical relevance). Around 15 NM before touchdown, an area with higher levels for flights using DYN-CAT is visible. However, segments where the L_{AE} is around 80 dB and above correspond to the area where the DYN-CAT function yields a reduction of the noise exposure. This is explained by the earlier excess energy dissipation with the use of DYN-CAT, resulting in a momentary increase in sound emission, and noise can, consequently, be reduced in later flight segments.

7.3 Limitations

The limited number of trials, pilots participating, and scenarios investigated obviously limits the universal validity of the results; notably, wind effects have not been taken into account. It is to be expected though that a predictive function taking (predicted) wind into account would be helpful for energy management, so the absence of wind in the experiments should lead to an underestimation of the benefits of the DYN-CAT support functions.

The level of technical knowledge and interest of the participants to the experiments, who were volunteers and typically had functions like technical or training pilots, in connection with their above-average familiarity with the test airport, can be assumed to lead to above-average performance in the reference case. The reference flights and therefore the comparison of results may contain a certain bias in this regard, as all approaches started from a high-energy situation and specified the Point of Descent (PoD). The real-world data analysis (Sect. 3 and [26]) 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 DYN-CAT function. Indeed, the pilot feedback generally acknowledges that such a solution will help to save fuel and to reduce noise emissions [35, 37].

The experiments were conducted under controlled conditions, with fuel flow and noise impact calculated. Any real-world measurement of the noise would suffer from measurement error through environmental noise interference, the

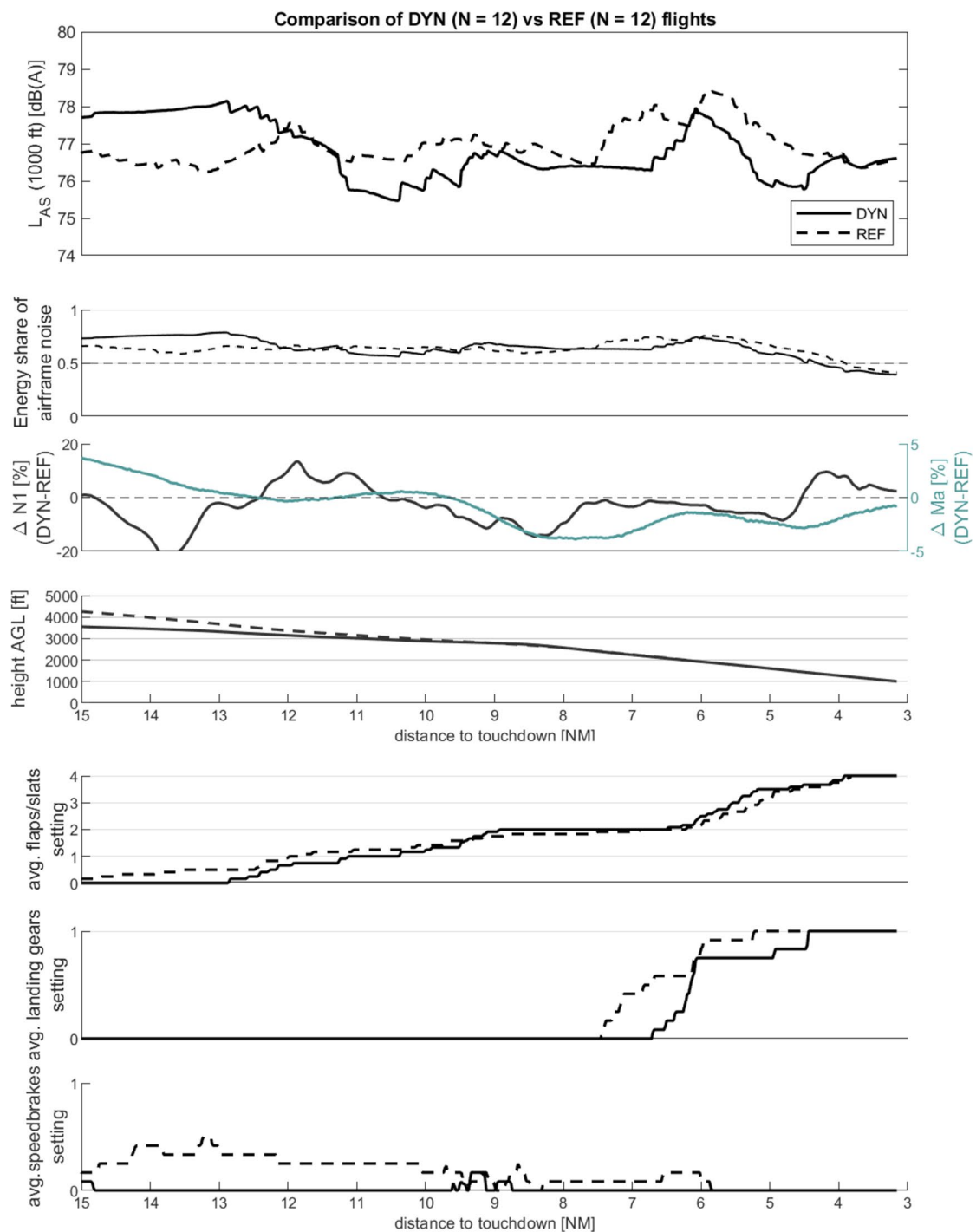


Fig. 12 Noise analysis and influencing parameters of 12 piloted simulation runs each with (solid lines) and without (dashed lines) DYN-CAT function: (top) sound pressure level LAS, obtained by simulations with a moving receiver, complemented with (from second to bottom): energy share of airframe noise against total noise; differ-

ences in engine fan speed N1 and Mach number Ma; height above airfield level; 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)

fact that noise can only be measured at a limited number of discrete locations, and differences in overflight altitudes. The chosen approach, on the other hand, avoids the first two effects and regarding the third one enables to investigate

noise emission and impact separately (Figs. 12, 13). This leads to a comparatively high trust in the accuracy of the results, especially as the engineering models for the engines

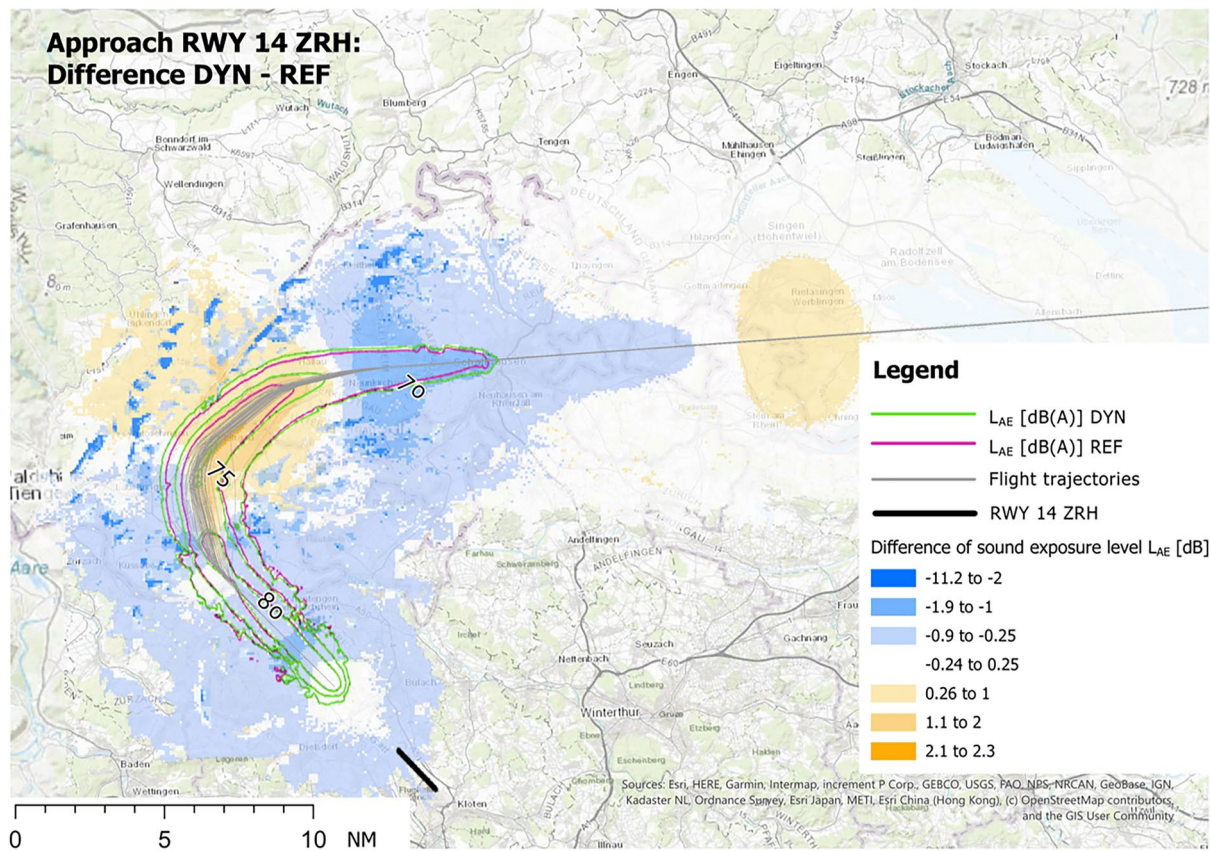


Fig. 13 Differential plots (averaged DYNCAT and reference flights; colour coded blue and orange) and noise contours (green and purple, resp.) of calculated sound exposure level L_{AE} at the ground. The solid black line depicts the runway

and the noise were effectively used to rate differences not absolute values.

Concerning methodology, a comprehensive environmental assessment would need to include non- CO_2 emissions (CO and HC) affecting mostly air quality, possibly through a minimum threshold for idle thrust [4]. This is a key factor to define a truly environmentally optimal descent and approach trajectory in terms of CO_2 emissions, non- CO_2 emissions, and noise. Given suitable idle thrust thresholds, probably with an altitude dependence, these could be easily integrated in the tool. For the present study, however, all changes to the procedures occurred above the stabilisation altitude at 1000 ft AAL, so that local air quality was not taken into account.

8 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 the new functionality and without it (which is the operational state of the art) 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. 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 DYN-CAT 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 DYN-CAT 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.

A comprehensive, structured list of recommendations for further maturation of the approach can be found in [41]. Suggested direct evolutions on the airborne system side comprise the FMS functions and CDS integration. Further work is especially required to develop the aircraft–ATM interfacing. A promising candidate is the concept of dynamic route structures [20] to accommodate the necessary individuality of trajectories. Support to fly safely and environmentally friendly while respecting given constraints is a first step, but the routing should allow more individualism to fly closer to the optimal procedure for the actual weight and weather situation. These two concepts benefit from each other, as the improved predictability of flight progress with the DYN-CAT support could decrease the necessity for ad-hoc ATC interventions. On the conceptual side, a full environmental optimisation would need to take non-CO₂ effects of the engine operation into account, notably the avoidance of low idle states at lower altitudes, e.g., through a minimum idle thrust threshold [4].

Acknowledgements The authors would like to recognise the expertise and contributions of the members of the DYN-CAT project advisory board. Special thanks for the valuable contributions and discussions with pilots and air traffic controllers received during the analysis of data set. The authors would also like to thank Swiss Airlines for the provision of the anonymous flight data sets.

Funding Open Access funding enabled and organized by Projekt DEAL. The DYN-CAT SESAR 2020 Exploratory Research project has received funding from the SESAR (3) Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 893568.

Data availability Not applicable.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. EUROCONTROL: Aviation outlook 2050. Main Report (2022)
2. European Commission: Reducing emissions from aviation (2020). https://ec.europa.eu/clima/policies/transport/aviation_en
3. European Commission: Updated analysis of the non-CO₂ climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4). Brussels (2020). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD:2020:277:FIN>
4. Otero, E., Tengzelius, U., Moberg, B.: Flight procedure analysis for a combined environmental impact reduction: an optimal trade-off strategy. *Aerospace* **9**(11), 683 (2022). <https://doi.org/10.3390/aerospace9110683>
5. Schäfer, A.W., Barrett, S.R.H., Doyme, K., Dray, L.M., Gnadt, A.R., Self, R., O'Sullivan, A., Synodinos, A.P., Torija, A.J.: Technological, economic and environmental prospects of all-electric aircraft. *Nat. Energy* **4**, 160–166 (2019)
6. N N. European Continuous Climb and Descent Operations (CCO/CDO) Action Plan. Eurocontrol, 6th November 2020
7. Gerber, M., Schreiber, Y., Abdelmoula, F., Kühne, C.G., Jäger, D., Wunderli, J.M.: Energy-optimized approaches: a challenge from the perspectives of pilots and air traffic controllers. *CEAS Aeronaut. J.* **13**, 1055–1066 (2022). <https://doi.org/10.1007/s13272-022-00607-0>
8. Scholz, M., Senske, V.: Auswirkungen unterschiedlicher Anflugverfahren auf den Treibstoffverbrauch auf Grundlage operationeller Flugbetriebsdaten (Effects of different approach procedures on fuel consumption based on flight operational data). In: German Aerospace Congress (DLRK), Friedrichshafen/Germany, 4th–6th September 2018, paper no. DLRK2018_480066
9. Sørensen, M., Münzel, T., Brink, M., Roswall, N., Wunderli, J.M., Foraster, M.: Chapter four—Transport, noise, and health. In: Nieuwenhuijsen, M.J., Khreis, H. (eds.) *Advances in Transportation and Health*, pp. 105–131. Elsevier (2020). <https://doi.org/10.1016/B978-0-12-819136-1.00004-8>
10. WHO: Burden of Disease from Environmental Noise. Quantification of Healthy Life Years Lost in Europe. Report, World Health Organization (WHO) Regional Office for Europe, 2011. NR, ISBN: 9789289002295
11. Kors, E., Collin, D.: Perspective on 25 years of European aircraft noise reduction technology efforts and shift towards global research aimed at quieter air transport. In: Leylekian, L., Covrig, A., Maximova, A. (eds.) *Aviation Noise Impact Management: Technologies, Regulations, and Societal Well-Being in*

- Europe, pp. 57–116. Springer International Publishing, Cham (2022). https://doi.org/10.1007/978-3-030-91194-2_4
12. Zellmann, C., Schäffer, B., Wunderli, J.M., Isermann, U., Paschereit, C.O.: Aircraft noise emission model accounting for aircraft flight parameters. *J. Aircr.* **55**(2), 682–695 (2018). <https://doi.org/10.2514/1.C034275>
 13. König, R., Schubert, E.: On the influences of an increased ILS glide slope on noise impact, fuel consumption and landing approach operation. In: 14th Australian International Aerospace Congress (AIAC14), Melbourne/Australia, 28th February–3rd March 2011
 14. Filippone, A.: Options for aircraft noise reduction on arrival and landing. *Aerosp. Sci. Technol.* **60**, 31–38 (2017). <https://doi.org/10.1016/j.ast.2016.10.027>
 15. König, R., Macke, O.: Evaluation of simulator and flight tested noise abatement approach procedures. In: 26th International Congress of the Aeronautical Sciences (ICAS 2008), Anchorage, Alaska/USA, 14th–19th September 2008. http://icas.org/ICAS_ARCHIVE/ICAS2008/PAPERS/365.PDF
 16. Thoma, E.M., Grönstedt, T., Otero Sola, E., Zhao, X.: Environmental assessment of noise abatement approach trajectories. In: 33rd International Council of Aeronautical Sciences (ICAS 2022), Stockholm, Sweden, 4th–9th September 2022
 17. Jin, L., Cao, Y., Sun, D.: Investigation of potential fuel savings due to continuous-descent approach. *J. Aircr.* **50**, 807–816 (2013). <https://doi.org/10.2514/1.C032000>
 18. Clarke, J.P.B., Ho, N.T., Ren, L., Brown, J.A., Elmer, K.R., Tong, K.O., Wat, J.K.: Continuous descent approach: design and flight test for Louisville international airport. *J. Aircr.* **41**, 1054–1066 (2004). <https://doi.org/10.2514/1.5572>
 19. Clarke, J.P., Brooks, J., Nagle, G., Scacchioli, A., White, W., Liu, S.R.: Optimized profile descent arrivals at Los Angeles international airport. *J. Aircr.* **50**(2), 360–369 (2013)
 20. Sáez, R., Polishchuk, T., Schmidt, Ch., Hardell, H., Smetanová, L., Polishchuk, V., Prats, X.: Automated sequencing and merging with dynamic aircraft arrival routes and speed management for continuous descent operations. *Transp. Res. C* (2021). <https://doi.org/10.1016/j.trc.2021.103402>
 21. Airbus: Getting to Grips with Aircraft Performance Monitoring. Flight Operations Support and Line Assistance, Blagnac/France (2002)
 22. Rodríguez-Díaz, A., Adenso-Díaz, B., González-Torre, P.L.: Improving aircraft approach operations taking into account noise and fuel consumption. *J. Air Transp. Manag.* **77**, 46–56 (2019). <https://doi.org/10.1016/j.jairtraman.2019.03.004>
 23. de Jong, P.M.A., de Gelder, N., Verhoeven, R., Bussink, F.J.L., Kohrs, R., van Paassen, M.M., Mulder, M.: Time and energy management during descent and approach: batch simulation study. *J. Aircr.* **52**(1), 1–14 (2014)
 24. Prats, X., Dalmau, R., Verhoeven, R., Bussink, F.: Human-in-the-loop performance assessment of optimized descents with time constraints—results from full motion flight simulation and a flight testing campaign. In: 12th USA/Europe Air Traffic Management Research and Development Seminar (ATM2017) (2017)
 25. Abdelmoula, F., Bauer, T.: Enabling environmentally friendly approach profiles—DYN-CAT. In: SESAR JU Webinar “Smart and Sustainable Solutions for Greener ATM—Greener Arrivals and Departures”. SESAR Digital Academy, online & Brussels/Belgium, 4th Dec 2020. <https://www.sesarju.eu/node/3704>
 26. Kühne, C.G., Scholz, M., Roeser, M.S., Jäger, D., Wunderli, J.M., Abdelmoula, F., Bauer, T.: SESAR 2020 DYN-CAT—D2.3—Critical Analysis of Current Operations. ed. 02.00.00, SESAR JU, 6th December 2022. <https://www.dyncat.eu/tabid-17143/>
 27. Abdelmoula, F., Roeser, M.S., Kühne, C.G., Gerber, M., Wunderli, J.M.: Impact of ATC speed instructions on fuel consumption and noise exposure: an assessment of real operations in Zurich. *CEAS Aeronaut. J.* (2022). <https://doi.org/10.1007/s13272-022-00609-y>
 28. Pauly, P., Gerber, M., Boyer, J., Wunderli, J.M., Abdelmoula, F., Bauer, T.: Improving energy state awareness during approach. In: German Aerospace Congress (DLRK) 2022, Dresden/Germany, 27th–29th Sep 2022, paper no. DLRK2022_570395
 29. Pauly, P., Meister, J., Wunderli, J.M., Gerber, M., Boyer, J., Abdelmoula, F., Bauer, T.: Improved energy management during arrival for lower noise emissions. In: Towards Sustainable Aviation Summit (TSAS), Toulouse/France, 18th–20th Oct 2022, paper no. 16
 30. Bauer, T., Abdelmoula, F., Boyer, J., Gerber, M., Meister, J., Wunderli, J.M.: Improved configuration management for greener approaches—evaluation of a novel pilot support concept. In: 33rd International Council of Aeronautical Sciences (ICAS 2022), Stockholm, Sweden, 4th–9th September 2022
 31. Kühne, C.G., Bauer, T., Roeser, M.S., Schiller, A., Gerber, M., Abdelmoula, F.: SESAR 2020 DYN-CAT—D2.5—Final Operational Concept Document. ed. 01.00.00, SESAR JU, 2nd August 2022. <https://www.dyncat.eu/tabid-17143/>
 32. Boyer, J., Dacre-Wright, B.: Permanent resume trajectory: an innovative flight management system functionality for greener and seamless operations. In: Aerospace Europe Conference 2020, Bordeaux/France, 25th–28th February 2020, paper no. AEC2020_493
 33. Boyer, J.: SESAR 2020 DYN-CAT—D3.4—Final System High-Level Specification. ed. 01.00.00, SESAR JU, 19th July 2022. <https://www.dyncat.eu/tabid-17143/>
 34. Durand, G., Boyer, J., Roger, M., Meister, J.: SESAR 2020 DYN-CAT—D3.2—Implementation Validation Plan. ed. 01.00.00, SESAR JU, 21st December 2021. <https://www.dyncat.eu/tabid-17143/>
 35. Boyer, J.: SESAR 2020 DYN-CAT—D4.1—Prototype Validation Report. ed. 01.00.00, SESAR JU, 4th July 2022. <https://www.dyncat.eu/tabid-17143/>
 36. N.N.: SESAR Environment Assessment Process—Environment Guideline, ed. 05.00, SESAR 3 JU, 23th July 2024
 37. Wunderli, J.M., Boyer, J., Meister, J.: SESAR 2020 DYN-CAT—D4.2—Environmental Benefits Report. ed. 01.00.00, SESAR JU, 4th July 2022. <https://www.dyncat.eu/tabid-17143/>
 38. Wunderli, J.M., Zellmann, C., Köpfl, M., Habermacher, M., Schwab, O., Schlatter, F., Schäffer, B.: sonAIR—a GIS-integrated spectral aircraft noise simulation tool for single flight prediction and noise mapping. *Acta Acust. United Acust.* **104**(3), 440–451 (2018). <https://doi.org/10.3813/AAA.919180>
 39. Zellmann, C.: Development of an aircraft noise emission model accounting for flight parameters (Doctoral thesis). Technische Universität Berlin, Berlin (2018). <https://doi.org/10.14279/depositononce-6712>
 40. Meister, J., Schalcher, S., Wunderli, J.M., Jäger, D., Zellmann, C., Schäffer, B.: Comparison of the aircraft noise calculation programs sonAIR, FLULA2 and AEDT with noise measurements of single flights. *Aerospace* **8**(12), 388 (2021)
 41. Gerber, M.: SESAR 2020 DYN-CAT—D5.1—Advanced Continuous Descent Operations—Recommendations and Roadmap. ed. 01.00.00, SESAR JU, 29th June 2022. <https://www.dyncat.eu/tabid-17143/>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.