

DYN-MARS: A New Concept Enabling the Best Approach Flight Profile

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Abstract

One of the most important challenges in modern aviation is improving efficiency while minimizing environmental impact. The Dynamic Management of Aircraft configuration and Route Structures (DYN-MARS) project directly addresses this challenge by focusing on reducing fuel consumption and noise emissions during the critical descent and approach phases, which are contributing significantly to a flight's environmental footprint. To achieve this, DYN-MARS brings together a multidisciplinary consortium of research institutions, aviation industry leaders, pilots and air traffic management experts, fostering collaboration across all levels of the aviation ecosystem. As a 3-year demonstration project under the Single European Sky ATM Research Programme (SESAR) Programme, DYN-MARS builds on prior SESAR innovations to introduce transformative solutions. These include e.g. optimized aircraft configuration and enhanced air-ground data exchange systems, enabling smoother, more predictable, and fuel-efficient descents. By combining airborne capabilities with Air Traffic Management (ATM) systems, DYN-MARS delivers a holistic, end-to-end solution that supports eco-friendly, optimized approaches. Overall, the DYN-MARS solution offers three main improvements, regarding fuel, noise and airspace capacity.

Keywords: Greener Flight Operations, Trajectory Optimization, Operational Efficiency, Environmental Benefit, Noise Reduction, Human Performance

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1. Introduction

Flightpath 2050 [1] is a strategic vision document published by the European Commission, outlining the future ambitions of aviation. It envisions a 75% reduction in CO_2 emissions per passenger kilometre and a 65% reduction of perceived noise emissions of flying aircraft by 2050, relative to the capabilities of typical new aircraft in 2000 [1]. This cannot be achieved by advances in engine technology alone and requires the contribution from all parts of the air transport system. In fact, the vision for "Protecting the Environment and the Energy Supply" states that "in parallel the air traffic control system is optimized to provide the best trajectories for fuel and time efficiency and associated atmospheric emissions and also to address noise. Noise projection on the ground is also reduced" [2].

A critical component of reaching the Flightpath 2050 targets is reducing flight inefficiencies, which are responsible for high amounts of CO_2 and noise emissions. Flight inefficiencies in terminal areas result in significant excess fuel consumption and emissions. These inefficiencies may be either of variable nature, caused by air traffic operations (e.g. tactical interventions), or of permanent nature, caused by the airspace design. Focusing on airspace, for the top 27 European airports in 2019, the cumulated fuel inefficiency reaches 194,000 tons for a total fuel burn of 880,000 tons in the last 50 NM[3]

The DYN-MARS project [4] is a European SESAR research initiative aimed at minimizing aviation's environmental footprint during descent and approach. Led by a consortium of international organizations — including the German Aerospace Center (DLR), the Netherlands Aerospace Center (NLR), Thales, Eurocontrol, NATS, Swiss SkyLab, Empa, and Swiss International Air Lines — the project focuses on improving collaboration between pilots and air traffic controllers to plan and execute more efficient flights. This collaboration will be supported by new avionics functions, as well as optimized arrival routes and procedures. DYN-MARS builds on earlier SESAR 2020 research, which developed concepts such as the Permanent Resume Trajectory (PRT) function, dynamic deployment of arrival route structures, and the Dynamic Configuration Adjustment in the TMA (DYNCAT) project [5]. Additionally, the project incorporates new air-to-ground data exchanges that enable better visibility of the flight plan both on the flight deck and on Air Traffic Control (ATC) screens.

The DYN-MARS project adopts a cascaded approach (see Figure 1) to air traffic improvements, aligned with the European Union's objectives of reducing the environmental impact of aviation:

- Short-term (2025-2030): the restructuring of routes will allow reduction of current flight inefficiencies e.g., during approach phases.
- Mid-term (2030-2040): combination of aircraft with enhanced FMS (within newly developed aircraft types or retrofitted to today's fleets) together with the proposed new ATM structures and procedures.
- Long-term (from 2040): full implementation of the DYN-MARS solution with new ATM structures, enhanced communication and most aircraft equipped with novel FMS

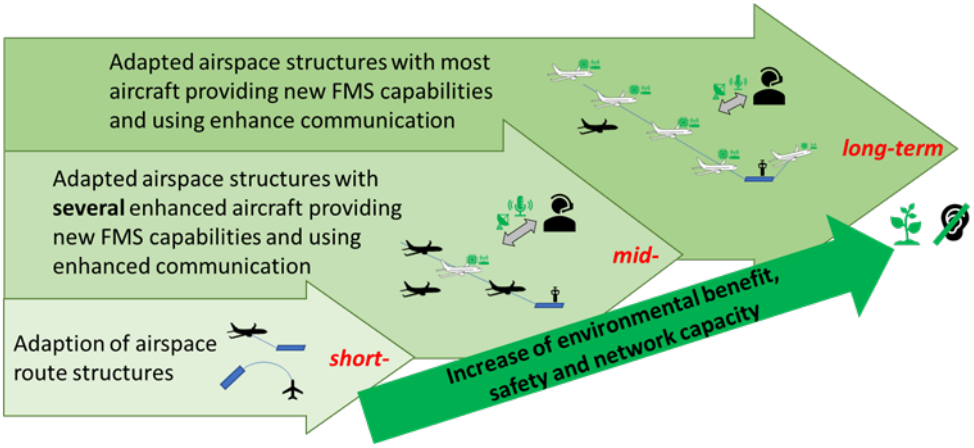


Figure 1 – Cascaded innovation approach for short-, mid- and long-term benefit using the DYN-MARS solution ([6]).

The following paper marks the begin of a series of papers and presentations, present the project overview and concept. It is going to explain the idea as well as the overall structure of the DYN-MARS project, with insides in the single campaigns and trials. The project's detailed results and analysis are going to be published in step by step in the upcoming papers throughout the next months.

1.1 State of the Art

In today's operation, ATM needs to manage the operation of many aircraft at a time safely and efficiently [5], which means to maintain minimum separation at all times, while maximizing arrival and departure rates at the same time. In dense terminal areas, controllers thus often need to use intermediate level-off, path stretching/shortening and speed instructions to ensure sequencing, separation and manage runway throughput. Noise abatement is considered by ATM mostly through generic procedures aiming at increasing the height of the flight path (raising intermediate altitudes, increasing glide path angle [7] and initial climb angles) and its horizontal distance from noise-sensitive areas [8]. Fuel efficiency and hence minimization of pollutants such as CO_2, NO_x has been accounted for by ATC for many years now, but opportunities to provide optimum fuel-efficient profiles are often reduced by separation and arrival sequencing considerations, plus the need to focus on capacity during peaks of traffic. It is obvious that the leeway controllers can give approaching aircraft considering their vertical, lateral and speed profiles is limited by the respective airspace structure. The design of the latter can hence play an important role in enabling environmentally friendly approach profiles.
On the other hand, pilots follow procedures laid down by the operator in the Flight Crew Operating Manual (FCOM) to achieve safe and efficient descent and landing operations of the individual aircraft. This means to follow a sequence of configuration changes (extension of the high-lift system in several steps, extension of the landing gear) with associated changes in airspeed. The ability to manage aircraft energy efficiently depends on a number of factors, but above all on the on-board availability of the remaining flight distance. [9].
On the technical side, all on-board support functions by current Flight Management System (FMS) need the definition of a lateral track as basis for altitude and speed predictions. In the absence of such information during ATC guidance by radar vectoring, which applies to the majority of operations, pilots are required to estimate the ratio between the current aircraft energy state and the remaining flight distance on their own. Air Traffic Controllers (ATCOs) confirm that radar vectoring is still indispensable for both sequencing and separation in most cases, and it therefore remains a fixed part of today's operations. However, in the absence of technical support, pilots tend to act over-conservatively which burns more fuel than technically possible.
A further aspect that has to be considered in this context is the communication between the flight crew and ATC. The information exchange between ground and airborne side during approach primarily relies on radio voice communication. Another disadvantage is, that this information is not directly fed to the avionic systems and thus cannot be used by FMS or other supporting systems without the intervention of the pilots. An already implemented digital data link between aircraft and ATC is the so called Controller-Pilot Data Link Communications (CPDLC). This protocol enables digital transmission of ATC clearances, turn headings, transponder code and hand-off instructions, but also enables the possibility to transmit requests from the aircraft to ATC. On a European basis these services are provided above flight level 285, while some other Air Navigation Service Provider (ANSP) like skyguide also cover more airspace. CPDLC is commonly used, for instance 23% of the traffic crossing the Maastricht Upper Area Control Center (MUAC) is using CPDLC on a daily basis. It acts as secondary communication medium, whereas voice communication remains the primary channel.

1.2 Previous Research

Building on its predecessors, the SESAR DYNCAT project [10] and the real-flight demonstrations of the SESAR project ALBATROSS [11], which delivered detailed analyses of descent and approach operations at major airports as well as early concept demonstrations (using Zurich as a case study), DYN-MARS derives its solution from the recommendations developed in that work.
The most important ATC mission is to ensure safety, while keeping approach optimization in mind as far as possible. Nevertheless, due to optimization being not a top priority, dedicated evaluations also showed, that some ATC instructions can result in additional fuel consumption or noise exposure, since a different, more efficient approach profile might have been used if no or less restrictions would have been given. For example, the analysis of the approach operations at Zurich Airport on Runway 14 revealed that the limited availability of integrated systems support for trajectory and flight state prediction on the flight deck compels pilots to adopt conservative approach strategies. This results in suboptimal performance, including increased noise levels and

higher fuel burn—particularly in areas such as aircraft configuration management, speed control, and the use of speed brakes [12]. These effects could be significantly reduced if an optimized approach profile were flown. It was also observed that deploying flaps far from the threshold results in a large noise footprint area. Early flap usage is often related to ATC speed instructions and/or early vertical instructions to descend. In order to comply with ATC instructions, pilots have to dissipate the aircraft total energy as soon as the instructions are given, and therefore, in addition to the aircraft limitations and operational envelopes, some configuration management combinations are used to dissipate altitude as quickly as possible, sometimes even on the cost of increasing the airspeed, if no speed limitation is given.

It has been shown in DYNCAT that even under similar conditions (same aircraft type, mass, weather, runway and even with equivalent ATC instructions) the approach profile in terms of speed management, high-lift system and landing gear configurations, as well as speed brake settings looks different among the pilots. This means, that many profiles do not represent the optimal solution with regards to fuel consumption and noise exposure. The reason for this is the high complexity of a task, where tactical interventions are often required by ATC to manage the traffic demand, making the actual trajectory hard to predict, combined with a lack of detailed vertical wind profile [12] .This is a big challenge even for highly experienced pilots, so that different pilots follow their individual energy dissipation strategies.

DYNCAT, further revealed that a variety of strategies has to be applied concerning speed regimes when optimizing vertical profiles and corresponding opposing trends can be expected when looking at lateral optimizations as well. E.g. a minimal fuel consumption can be expected when taking the shortest possible flight path, which might lead to a higher noise burden on the other side [12]. Hence, the DYN-MARS solution will focus on this challenge and come up with situation specific optima with the goal of minimizing all environmental issues integrally.

2. Solution Description

The DYN-MARS project builds up on the preliminary conclusions of DYNCAT (Dynamic Configuration Adjustment in the TMA) project and delivers a solution composed of two key parts (see Fig. 2). The first part involves an FMS, designed to optimize flight operations. This system dynamically calculates the required aircraft configuration (in terms of high-lift systems), allowing the aircraft to follow the lateral path of a PRT and a newly optimized vertical profile. The autopilot can manage this process by either flying in full-managed modes or following the pilots inputs in a (semi-)manual flight, where the pilots make adjustments as needed. Modern aircraft flight control systems are well-equipped to integrate these FMS enhancements, enabling short- and medium-term retrofitting of existing fleets. Additionally, advanced communication methods will facilitate the necessary data exchange between the aircraft and ground systems, enabling these enhanced functionalities.



Figure 2 – Two parts of the DYN-MARS ambition: enhancements on ATM and airborne side connected by the implementation of novel communication ([6]).

The second part is based on new airspace management techniques and the development of related support tools. These innovations aim to optimise aircraft routing within the Terminal Manoeuvring Area (TMA), increasing airspace capacity while simultaneously promoting more environmentally efficient operations, without compromising current safety standards. While the DYN-MARS solution primarily focuses on improving arrival procedures, it also considers departures, as they significantly influence the overall network's performance. For instance, based on the uplink of a (dynamically assigned) Standard Instrument Departure (SID), Standard Terminal Arrival Route (STAR) or approach via CPDLC, DYN-MARS aims to allow pilots to better plan their optimum descent profile while ATC will ensure separation with potentially conflicting aircraft. In the other direction, a downlink of the FMS computed trajectory through Automatic Dependent Surveillance Contract (ADS-C) could further ease the optimisation process of aircraft trajectory between aircraft and ATM. Both parts are connected by novel ways of communication between flight crew and ATCOs (oral and/or via data link) if/when needed to ensure the applicability of the new developments and procedures in the complex ATM environment.

DYN-MARS is a solution that approaches optimisation holistically as an ecosystem between aircraft and ATC. The uncertainty of the four-dimensional flight path is reduced sequentially in 3 levels:

Level 1 (hours): Current published STARs and Area Navigation (RNAV) transitions are primarily designed to accommodate peak air traffic demand. As a result, these procedures often include relatively long flight paths to provide sufficient flexibility for sequencing and spacing, commonly referred to as path stretching capability. From the perspective of an individual aircraft, this capability translates into uncertainty in the actual distance flown from the start of the approach to the runway threshold. Within Level 1 of the DYN-MARS solution, a set of alternative RNAV transitions is introduced to address this inefficiency. These so-called Dynamic Route Structuress (DRSs) and Offload STARs are designed to reduce the maximum path stretching capability throughout the day by offering shorter route options. They can be selectively activated during periods of lower traffic demand, when extensive path stretching is no longer necessary, thereby improving flight efficiency and reducing environmental impact.

Level 2 (minutes): Even after an aircraft has been cleared for a RNAV transition, a degree of path stretching capability remains present in the procedure. To ensure the aircraft reaches an optimal energy state, it is therefore necessary to further reduce uncertainty in the lateral trajectory. This is achieved through an uplink from the approach controller, providing the aircraft with the expected lateral path. The shortcut information is then used to accurately assess the aircraft's energy state and generate corresponding Human Machine Interface (HMI) cues to guide the aircraft along an optimal descent profile. Based on this initial trajectory estimate, the aircraft can initiate an efficient, optimized descent. As a result of this Level 2 concept, one degree of freedom in the aircraft trajectory is effectively removed. The remaining degrees of freedom are then limited to the vertical profile and speed profile, enabling more precise and efficient flight execution.

Level 3 (seconds): Once the lateral path uncertainty has been reduced, maintaining adequate separation re-

quires introducing a degree of flexibility for the approach controller through speed interventions. However, any such intervention inevitably alters the initially planned vertical and speed profiles, leading to deviations from the optimal descent trajectory. Some speed interventions can be accommodated with minimal impact on overall efficiency, preserving near-optimal performance in terms of fuel consumption and noise, while others can significantly disrupt an optimized descent. For example, a reduction from clean configuration speed to the minimum-drag intermediate configuration speed required for a 3° glide-path must be initiated before the aircraft is established on the glide-path. If applied too late, this reduction can necessitate the use of additional drag devices, such as speed brakes or landing gear, thereby reducing efficiency and increasing both fuel burn and noise.

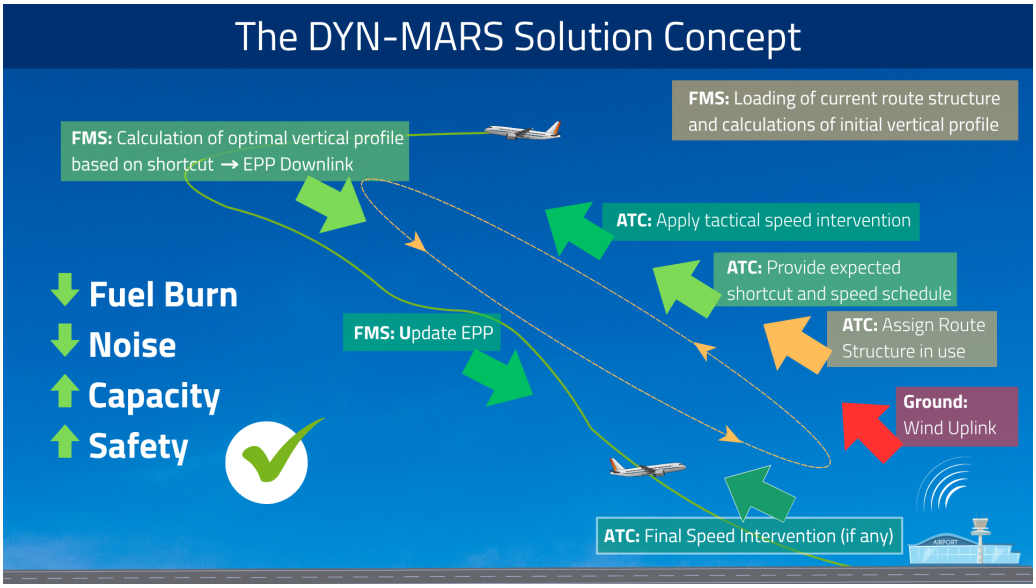


Figure 3 – DYN-MARS concept visualization ([6]).

Level 3 of DYN-MARS solution introduces a solution to continuously compute the optimum vertical profile within the FMS in response to airspeed changes assigned by ATC. In addition, the enhanced FMS determines the optimal positions for configuring the aircraft (e.g. deployment of flaps, slats, and landing gear). These predicted configuration points support pilots in managing the aircraft's energy state and help ensure proper stabilization at the defined stabilization altitude (typically 1'000 ft or 500 ft Above Ground Level (AGL)).
Finally, to close the loop with air traffic control, key trajectory predictions—such as the default deceleration locations are downlinked via ADS-C-Extended Projected Profile (EPP). These data can be integrated into Time-Based Separation (TBS) tools, enhancing controller situational awareness and enabling more precise and efficient traffic management. The DYN-MARS concept is further illustrated in Fig. 3.

3. Validation Exercises

In order to optimise aircraft operations and reduce the environmental footprint, DYN-MARS identified three primary objectives that were addressed in a set of five exercises. First, descent profile planning and execution — both lateral and vertical — must be dynamically optimized to significantly enhance the efficiency of the descent and approach phases for each aircraft. This optimization made a combination of advanced avionics, improved controller tools, and expanded air-ground data sharing necessary. The expected benefits include a up to 10% reduction in CO_2 emissions and fuel consumption during descent and approach, along with at least a 1dB(A) reduction in the average sound pressure exposure level on the ground (Objective 1).
Second, Performance Based Navigation (PBN) route structures for arrivals and departures must be dynamically adjusted to meet operational requirements and prevailing conditions. This goal was achieved through an integrated approach that combined optimized airspace design, enhanced controller tools, onboard aircraft systems, and improved communication protocols. The dynamic adjustment aimed to improve network flight efficiency and environmental performance, addressing the current 41% fuel inefficiency (Objective 2).
Finally, DYN-MARS addressed the impact of FMS-defined arrivals on ATM operations in the TMA. This included real-time simulations and safety assessments to evaluate the feasibility and operational impact of the proposed solution, ensuring that safety and performance standards are maintained while providing ATCOs with actionable insights (Objective 3).

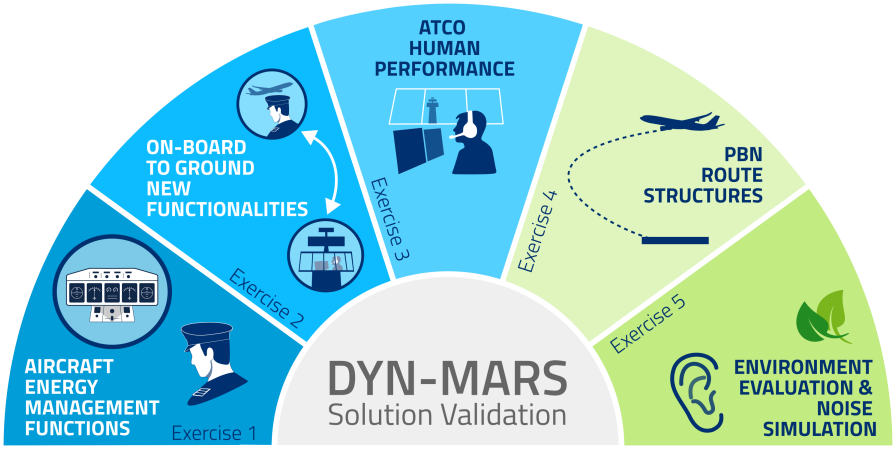


Figure 4 – DYN-MARS exercise structure for solution validation ([6]).

The benefits were demonstrated by comparing the current state of the art with the proposed solutions across three key performance indicators: fuel consumption and associated CO_2 emissions, ground noise footprint and community noise exposure, and airspace capacity. In addition, further indicators such as ATCO and Flight Crew workload were assessed in relation to project processes and tools, both ground-based and onboard aircraft, to ensure that safety levels are maintained or improved.

3.1 Exercise 1 - FMS Functionality

Exercise 1 focused on a single aircraft operating within the TMA, without interaction from surrounding traffic. Within this controlled environment, the solution was required to meet three primary objectives. First, the onboard system had to compute and accurately follow an optimized vertical profile, satisfying constraints on altitude, speed, and Flight Path Angle (FPA). In addition, it was required to determine the optimal points for configuration changes (Conf1, Conf2, landing gear deployment, Conf3, and Conf Full), while maintaining minimum thrust, avoiding the use of speed brakes, and complying with ATC instructions. Second, enhancements related to the handling of ATC interventions were evaluated. The scenarios were specifically designed to expose pilots to situations in which advanced FMS functionalities such as Radar Vectoring, Distance-To-Go (DTG) and tactical speed interventions became active. Third, the exercise assessed newly introduced energy-awareness cues. These cues provide lateral and vertical guidance in both selected and managed flight guidance modes, supporting flight crews in maintaining the optimal descent profile.
To evaluate the mentioned functionalities (which also included functional testing by Skylab in 3.2), both Thales and DLR conducted an extensive real-time simulation campaign at the DLR facility in Brunswick, using the Air Vehicle Simulator (AVES) full-flight simulator. The campaign comprised 14 distinct scenarios, each executed

in two configurations: a baseline version using the current state of the art FMS produced by Thales (also called PureFlyt FMS S2) and a solution version, which is based on the PureFlyt FMS including enhancements needed for to reach the project's goals (also called DYN-MARS FMS). The scenarios varied in key flight parameters, including location, cruise flight level, landing weight, cost index and wind conditions. Each scenario was executed multiple times (at least five repetitions for high-priority cases and two for medium-priority ones) by different flight crews, with each crew executing up to 8 different scenarios. In total, more than 50 airline pilots, primarily from Lufthansa and Eurowings, participated in the campaign and executed over 100 simulated flights, with promising results in terms of fuel efficiency. (See also: Tab. 1).
The selected airports were distributed across Western Europe and chosen based on their specific approach characteristics. Radar Vectoring scenarios were conducted at Berlin (Germany - EDDB), while Open Path Procedures were tested at Paris (France - LFPG). Dynamic Route Structures were evaluated at three airports: Zurich (Switzerland - LSZH), featuring a trombone approach; Dublin (Ireland - EIDW), with a point merge procedure; and Malaga (Spain - LEMG), with a folded trombone configuration. Finally, the compatibility of the DYN-MARS FMS with PBN-to-xLS approach procedures was assessed at Vienna (Austria - LOWW).

3.2 Exercise 2: ATC-Pilot Information Exchange

The second exercise was structured around two main objectives: (i) to assess the individual benefits of each part of the solution, and (ii) to evaluate the overall performance of the DYN-MARS solution within a complex operational environment. The exercise began with a stand-alone real-time simulation in the AVES, focusing exclusively on the novel FMS functionalities in a controlled, simulated, high-traffic scenario where speed instructions are assigned tactically by the ATCO. The exercise was extended to a federated real-time simulation afterwards, where the new FMS functionalities and communication capabilities were integrated into a realistic traffic environment.

3.2.1 Standalone Simulations

This campaign was designed to validate the individual solution items in a systematic, step-by-step manner in a highly realistic operational environment with the same type and frequency of tactical ATC instructions. In contrast to the previously described exercise, all scenarios were conducted at the same airport and under identical weather conditions. This controlled setup enabled a precise assessment of the impact of individual parameters as they were varied across the scenarios. The validation scenarios spanned across all solution elements such as radar vectoring and closed-path navigation, different types of speed instructions, provision of lateral path information for aircraft energy management and assessment of HMI cues. All in all, almost 300 flights have been executed between July and October 2025 by more than 50 pilots in order to generate a statistically sufficient dataset.

3.2.2 Federated Simulations

The primary objective of this campaign was to assess the benefits of early aircraft trajectory determination for optimized descent operations in a federated simulation with multiple simultaneous actors from full-flight and desktop simulation stations. To this end, researchers at DLR established a representative traffic environment comprising both DYN-MARS-equipped aircraft and conventionally equipped aircraft with current standard FMS functionalities. Both aircraft types operated within the same airspace, reflecting the mixed-equipage conditions expected in future operations. To enable this complex setup, multiple simulator stations and system instances were interconnected. ATC operations were simulated using the Air Traffic Management and Operations Simulator (ATMOS) operated by DLR [13], with surrounding traffic managed by two DLR engineers acting as pseudo-pilots. The DYN-MARS-equipped aircraft were operated via the AVES simulation environment, which included a full-flight A320 cockpit simulator, staffed by two airline pilots and one DLR engineer, as well as five desktop simulators, each operated by either a DLR engineer or a Skylab pilot. Including additional support roles (software specialist, hardware specialist, and coordinator), each simulation run required a team of 14 persons.
The campaign included trial runs at two airports: Berlin (Germany - EDDB), and Zurich (Switzerland - LSZH). These locations were selected based on the availability of suitable published arrival procedures. For each airport, realistic traffic scenarios were generated by identifying inbound aircraft over a period of approximately two to three hours and compressing them to achieve a traffic density of around 30 aircraft per hour, necessitating

structured arrival management. Each aircraft was assigned an initial state (position, altitude, speed, etc.), a start time, and a default arrival route.

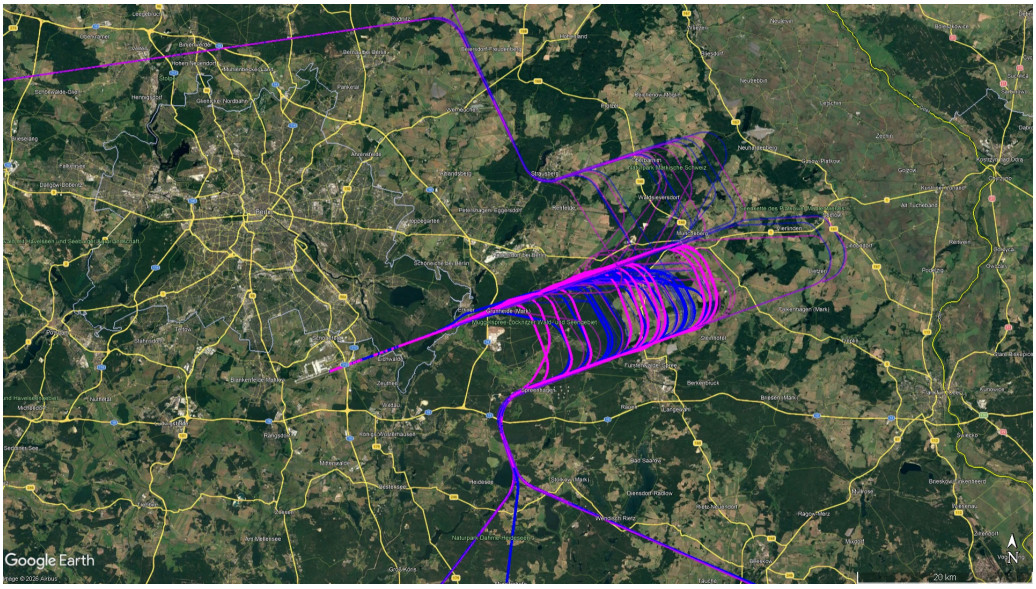


Figure 5 – Exercise 2 Example Tracks: comparison of reference and solution flights for one specific controller and one scenario run each; AVES Cockpit flights (opaque lines) and ATMOS flights (translucent lines) ([6]).

For both airports, two scenario types were defined: a reference scenario and a solution scenario. In the reference scenario, ATCOs applied current standard operating procedures, issuing radar vectoring instructions via voice communication to all aircraft. In the solution scenario, ATCOs differentiated between DYN-MARS-equipped and conventionally equipped aircraft. Conventional aircraft continued to receive radar vectoring instructions via voice, while DYN-MARS-equipped aircraft were managed through a combination of CPDLC route uplinks and voice communication. The concept aimed to provide aircraft with early trajectory information (such as expected shortcuts) after which no further tactical interventions were required, allowing the aircraft to autonomously manage their descent. The resulting 4D trajectories (position, altitude, speed, and time) were downlinked to ATC to support controller situational awareness.
In total, 25 simulation runs to Berlin were conducted over a two-month period at DLR. Of these, 16 runs were managed by ATCOs from Deutsche Flugsicherung (DFS), while 9 runs were conducted by DLR controllers. This resulted in 411 reference flights (133 performed on the AVES cockpit simulator and 298 via ATMOS pseudo-pilot stations) and 525 solution flights (171 on AVES and 354 via ATMOS), yielding 304 flights suitable for detailed analysis of DYN-MARS functionalities (see Fig. 5[1]). In addition, four simulation runs were conducted for Zurich Airport to validate the findings in terms of fuel efficiency (see Tab. 1) and human workload obtained from the Berlin campaign.

3.3 Exercise 3: ATCO Human Performance and Safety

The focus of Exercise 3 was on human performance from the ATCO perspective. To investigate this topic, NLR conducted a real-time simulation using the NLR Air Traffic Control Research Simulator (NARSIM) to assess the operational feasibility of the DYN-MARS solution and its impact on controller performance. Particular attention was given to separation management. Longitudinal separation was evaluated for sequences of FMS-defined arrivals, while vertical separation was assessed at route crossings between FMS-defined arrivals and departing traffic, including the potential need for enhanced vertical clearances.

[1]Google Earth is a trademark of Google LLC

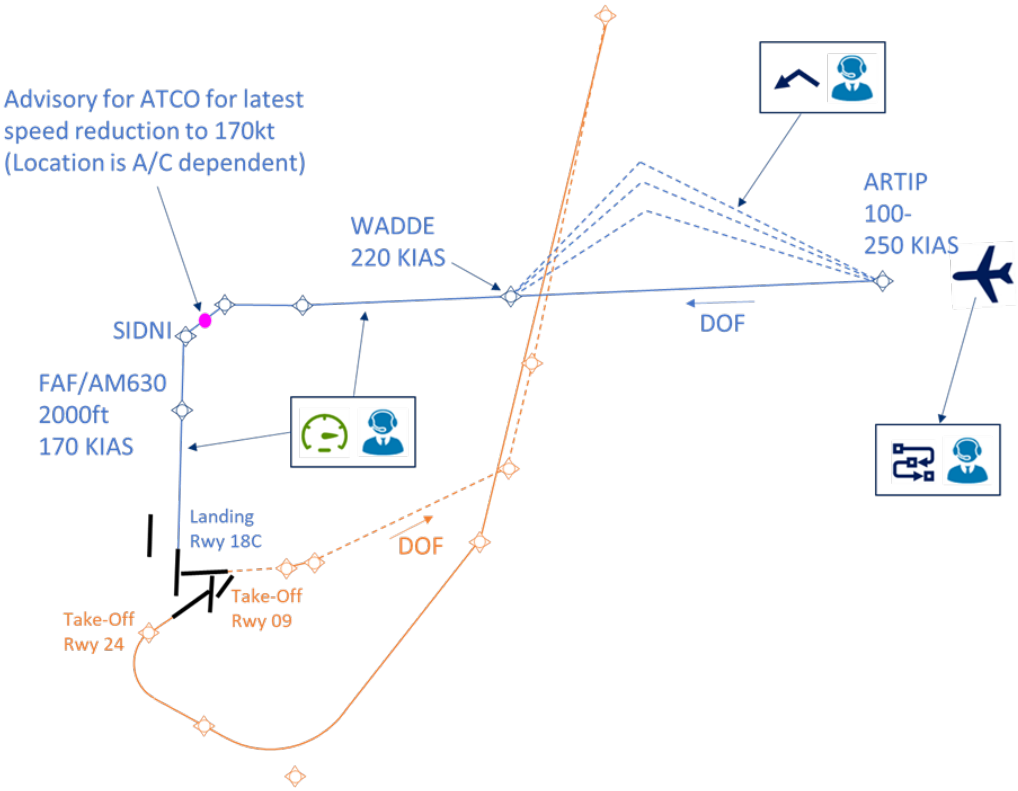


Figure 6 – Exercise 3 Solution Scenario ([6]).

The operational environment was based on the Amsterdam Schiphol (Netherlands - EHAM) TMA projected for 2030+. The scenario incorporates SID procedures for outbound traffic and Fixed Arrival Route (FAR) procedures for inbound traffic. The simulation setup (see Fig. 6) included two approach control working positions, reflecting standard operations in the Schiphol TMA:

- A Feeder/Departure Controller (FDR/DCO), responsible for managing aircraft from the Terminal Entry Point (TEP)
- An Arrival Controller (ARR), responsible for handling aircraft handed over by the FDR/DCO

The FDR/DCO was primarily tasked with resolving inbound–outbound conflicts while establishing initial spacing. The ARR controller was responsible for sequencing aircraft onto the final approach path, managing high traffic demand while maintaining aircraft on the FAR procedure. The arrival phase began at the TEP, with aircraft being typically at approximately FL100. Between the TEP and the start of the FAR, controllers were allowed to apply radar vectoring to achieve the required spacing. Aircraft then joined the FAR at FL60 or above, after which they remained on the predefined route.
The traffic sample represented a high-density inbound peak period, based on historical traffic data from Schiphol and reflecting a realistic mix of aircraft types. Two equipage scenarios were evaluated: a low equipage level, with approximately 20–30% of aircraft equipped with the DYN-MARS FMS, and a high equipage level, with approximately 70–80% of aircraft equipped. In the end, a positive effect of about 10% airspace capacity increase in Medium and High Complexity TMAs has been observed.

3.4 Exercise 4: PBN Route Structures for Arrivals and Departures

This exercise was conducted to achieve a comprehensive validation of DRS within the Stansted (England - EGSS) TMA. The campaign relied on four complementary simulation environments: A Fast-Time Simulation (FTS) using AirTOP [14] and DesignAir, a Part-Task Trainer (PTT) for usability assessment and concept refinement, a stand-alone Real-Time Simulation (RTS) to obtain measured results and ATCO feedback, and a federated RTS to collect data for fuel consumption and noise analysis.
The campaign was divided into two phases. The first phase, led by NATS and EUROCONTROL, focused exclusively on DRS and included the FTS, PTT, and stand-alone RTS activities. The second phase extended

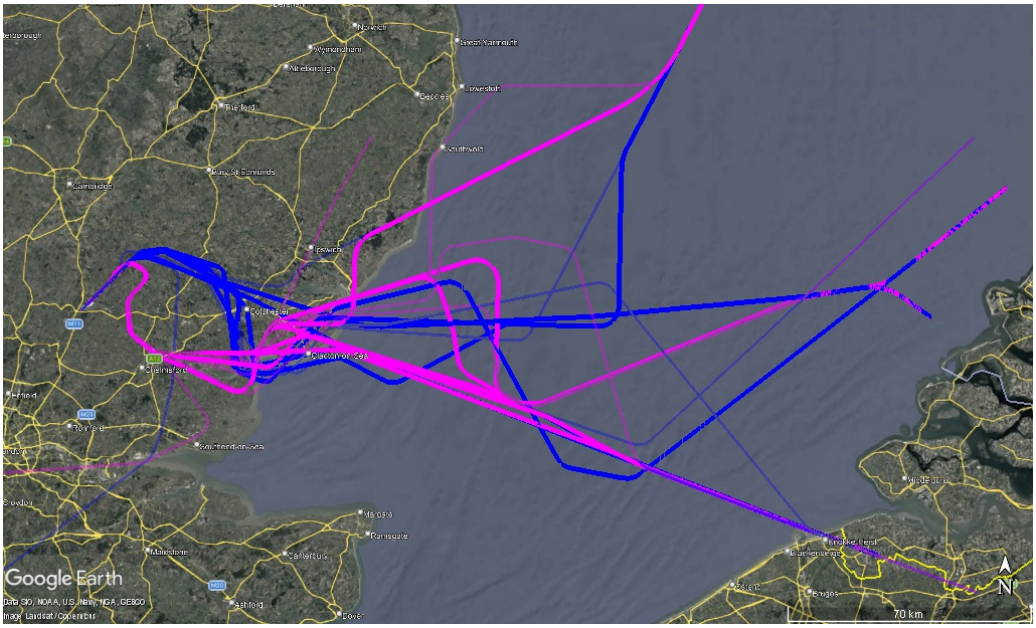


Figure 7 – Comparison of flight tracks for reference (blue) and solution (magenta) flights; AVES flights (opaque lines) and ESCAPE flights (translucent lines) ([6]).

the concept by integrating dynamic individual flight trajectories, incorporating multiple flight simulation environments equipped with the DYN-MARS solution and operated by DLR. As previously described, this setup comprised six simulators: one full-flight simulator and five desktop simulators (see 3.2.2). The federated RTS was conducted in the airspace surrounding London Stansted (England - EGSS) and featured a set of ten custom-designed STARs, guiding aircraft arriving from the north-east toward a northern point-merge arc. Flight tracks for one example of the peak traffic scenario are given in Fig. 7[2]. To evaluate the proposed concept, NATS developed five traffic scenarios: high traffic, low traffic, peak traffic, and transition scenarios from high to low and low to high traffic densities. Each scenario was implemented in two configurations: a reference scenario based on conventional radar vectoring, and a solution scenario utilizing closed-path dynamic routes.
To support the federated simulation, the six DLR simulators were interconnected with the ESCAPE ATC simulator at EUROCONTROL in Brétigny, complemented by ESCAPE pseudo-pilot stations. Each simulation run required a team of 14 operational staff, supported by additional technical specialists. The operational team consisted of:

- two pilots operating the AVES full-flight simulator,
- one AVES simulator operator,
- five desktop pilots operating the AVES desktop simulators,
- two pseudo-pilots managing the ESCAPE pseudo-pilot stations,
- two air traffic controllers working in the ESCAPE ATC simulator, and
- two coordinators (one based in Germany and one in France).

During the validation task runs in December 2025, all 10 scenarios (reference and solution) were executed with a total of 12 federated simulation runs on 3 days. This resulted in 52 reference flights (30 performed on AVES and 22 via ESCAPE) and 60 solution flights (33 on AVES and 27 via ESCAPE). From these, 63 AVES flights were identified as suitable for detailed analysis of DYN-MARS-enabled FMS performance.

[2]Google Earth is a trademark of Google LLC

3.5 Exercise 5: Environmental Benefit Analysis

The environmental benefit analysis represents the final stage of the project and focuses on the environmental benefits achieved by the proposed solution during descent and approach phases. Performance is evaluated in terms of fuel consumption and noise impact. To quantify these benefits, results from the previously described exercises (3.1, 3.2, and 3.4) are consolidated and further processed using flight data generated from both RTS and FTS results. Fuel consumption benefits are directly derived from the RTS and FTS outputs. The DYN-MARS solution consists of different novel developments on airborne and ground side. Hence, the resulting benefit on fuel is different for each enabler[3] validated in the different exercises. In addition, from an operational perspective it is relevant to define a representative reference point along the approach trajectory to measure the benefit. This reference was different in DYN-MARS exercises according to the given validation scenario. The exercise related fuel savings are given on Tab. 1 for the specific tested DYN-MARS functions/enablers. The DYN-MARS solution reduces the average CO_2 emissions in the order of 8.7 % ($\approx$ 63 kg) over the last 40 to 45NM, which is a rounded average of the different exercise (1, 2 & 4) results.

Exercise	Simulation	Reference	average fuel saving relative	average fuel saving absolute	comment
#1	RTS	arrival	4.7 %	16 kg	enhanced FMS
#2	RTS	45 NM	8.4 %	19 kg	new communication, enhanced FMS
#4	stand-alone RTS	scenario	10.0 %	-	new route structures
	federated RTS	42 NM	4.1 % - 22.3 %	7 kg - 47 kg	new route structures & enhanced FMS (depending on scenario)

Table 1 – Fuel savings for different DYN-MARS functions/enablers resulting from the different solution validation exercises ([6]).

The noise assessment is conducted in two steps. First, for each aircraft type and landing route, a representative noise impact is derived by averaging the sound exposure over multiple flights of the same aircraft type on a given route. Prior to averaging, level distributions are analysed to identify and exclude potential outliers. In the second step, the aggregated results are extrapolated to annual traffic volumes for each route. Based on this upscaling, an assessment of the number of highly annoyed and highly sleep-disturbed inhabitants is performed. The evaluation shows a positive regarding the noise contour area, that could be decreased by around 19%, as well as a reduction of the number of affected people by up to 15% across the airports of Zurich, Berlin and London. More details will be published in following papers.

[3] the most comprehensive benefit results from the common application of all individual enablers

4. Summary and Prospects

To validate the DYN-MARS solution, an extensive campaign was conducted by all consortium partners. In total, five distinct exercises were carried out, comprising both real-time and fast-time simulation activities. Across the campaign, more than 70 pilots participated in over 60 scenarios, supported by 5 air traffic controllers. In the real-time simulations alone, approximately 950 individual flights were performed, generating a comprehensive dataset of flight data and qualitative feedback from both pilots and controllers. The analysis of this extensive dataset shows that the DYN-MARS solution successfully demonstrated its ability to facilitate aircraft separation and sequencing of arrival flows, while demonstrating a positive impact on human performance at the same time. The analysis on from ground perspective shows that the DYN-MARS solution demonstrated potential on the ATM side, but also pointed out, that certain areas, especially those containing the controllers' capability to adapt in abnormal conditions, need further development. On the airborne side, the results indicate a reduction in crew-workload and an improvement in situational awareness. It has been shown, that the overall DYN-MARS solution can achieve an acceptable level of operational safety, with the exception of DRS, where additional enhancements are needed.

Overall, the DYN-MARS solution offers three main improvements, regarding fuel, noise and airspace capacity. First of all, there is a potential fuel saving of approximately 10% during descent and approach, equalling about 20kg of fuel per flight, without effects on the planned flight duration. Secondly, the noise contour area could be decreased by around 19%, reducing the number of affected people by up to 15% across the airports of Zurich, Berlin and London. And last but not least, a +10% airspace capacity increase in Medium and High Complexity TMAs has been observed.

A key advantage of the DYN-MARS solution is that its benefits can be realised across both current and future aircraft generations. This is because the reduction in fuel burn is primarily achieved through improved operational procedures rather than changes to the propulsion system itself. Consequently, the solution targets air traffic management aspects and optimised flight procedures, with the aim of reducing the environmental impact of aviation.

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7. List of Abbreviations

ADS-C	Automatic Dependent Surveillance Contract
AGL	Above Ground Level
ANSP	Air Navigation Service Provider
ARR	Arrival Controller
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATM	Air Traffic Management
ATMOS	Air Traffic Management and Operations Simulator
AVES	Air Vehicle Simulator
CPDLC	Controller-Pilot Data Link Communications
DFS	Deutsche Flugsicherung
DLR	German Aerospace Center
DTG	Distance-To-Go
DRS	Dynamic Route Structures
DYNCAT	Dynamic Configuration Adjustment in the TMA
DYN-MARS	Dynamic Management of Aircraft configuration and Route Structures
EPP	Extended Projected Profile
FAR	Fixed Arrival Route
FCOM	Flight Crew Operating Manual
FDR/DCO	Feeder/Departure Controller
FMS	Flight Management System
FPA	Flight Path Angle
FTS	Fast-Time Simulation
HMI	Human Machine Interface
MUAC	Maastricht Upper Area Control Center
NARSIM	NLR Air Traffic Control Research Simulator
NLR	Netherlands Aerospace Center
PBN	Performance Based Navigation
PRT	Permanent Resume Trajectory
PTT	Part-Task Trainer
RNAV	Area Navigation
RTS	Real-Time Simulation
SESAR	Single European Sky ATM Research Programme
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
TBS	Time-Based Separation
TEP	Terminal Entry Point
TMA	Terminal Manoeuvring Area

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