

A Fast and Flexible Aircraft Trajectory Predictor and Optimiser for ATM Research Applications

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Abstract—Trajectory prediction and optimisation algorithms will be the keystone for a successful trajectory based operations concept implementation, where accurate predictions and optimal trajectories will be needed for a wide variety of look-ahead times and operational contexts. The main goal of this paper is to present the architecture and capabilities of an aircraft trajectory prediction and optimisation framework suitable for various air traffic management research applications. The flexibility of this framework, called DYNAMO, allows for an easy implementation and assessment of actual and future concepts of operation, considering at the same time realistic weather data and aircraft performance models. In addition, its design enables the use for real-time applications and when a large set of trajectories needs to be rapidly generated for simulation and benchmarking purposes. The performance of the framework is demonstrated by means of different illustrative examples.

I. INTRODUCTION

With the initiatives proposed by the programmes SESAR (Single European Sky ATM Research) and NextGen, in the United States of America, a series of challenges and new concepts of operations are currently under development. Among them, the implementation of Trajectory Based Operations (TBO), allowing airlines to plan and execute their preferred trajectories subject to minimum Air Traffic Management (ATM) constraints.

State-of-the-art trajectory predictors, used by most airline planning tools and on-board Flight Management Systems (FMS), compute trajectories by numerically integrating the equations of motion, which describe the aircraft dynamics, given a set of flight intents (such as tabulated speed and altitude schedules) [1]. In a trajectory optimisation problem, however, these flight intents become unknowns and must be determined such that a certain cost function is minimised, while still satisfying a set of constraints.

Trajectory optimisation algorithms have been subject of research for several decades, and a wide variety of trajectory optimisation frameworks with different capabilities and designed for various purposes can be found in the literature (see for instance [2] and the references therein). The main

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difficulties encountered by most state-of-the-art frameworks are: to formulate in a single problem the optimisation of the vertical profile (where continuous aircraft dynamics constraints apply) and the lateral route (typically described by a discrete sequence of waypoints); to incorporate realistic weather and aircraft performance models; and to be flexible enough such that various lateral and vertical Concepts of Operations (ConOps) can be considered with minimum modelling effort. Real-time and scalability aspects might also be a limiting factor for certain applications or assessments.

In Ref. [3], the lateral route and vertical profile were simultaneously optimised with a single optimal control problem formulation, which was solved by means of Mixed-Integer Non-Linear Programming (MINLP). This strategy provides accurate results, but is very computationally expensive. Aiming at overcoming this issue, Ref. [4] proposed a multi-step approach that decouples the optimisation of the lateral route and vertical profile: first, the optimal route is computed using shortest path algorithms (e.g. A-star); then, the vertical profile is optimised using a flight performance model build on COALA (COMpromised Aircraft performance model with Limited Accuracy) [5]. Another example of decoupled trajectory optimisation method, in which A-star is used for both lateral and vertical domains, was proposed in Ref. [6].

In a previous work ([7]), a prototype of a highly-scalable ATM simulator was presented, based on a high performance computing software and hardware architecture. The trajectories of this simulator are generated by DYNAMO (DYNAMic Optimiser), a trajectory prediction and optimisation framework capable to rapidly compute trajectories using realistic and accurate weather and aircraft performance data. Moreover, DYNAMO is highly flexible and configurable and allows the user to easily specify a great variety of operational and/or ATM constraints. This allows to model realistic operational procedures as well as the implementation of several ConOps: from (futuristic) unconstrained Continuous Cruise Climbs (CCC) flying in a complete free route airspace, to conventional operations in structured route networks and using flight level allocation and orientation schemes.

Some insights on DYNAMO have been previously published (see for instance [8], [9], [10]). This paper aims to unify the description of the software architecture, the mathematical modelling behind, and the list of capabilities, assumptions and limitations of DYNAMO.

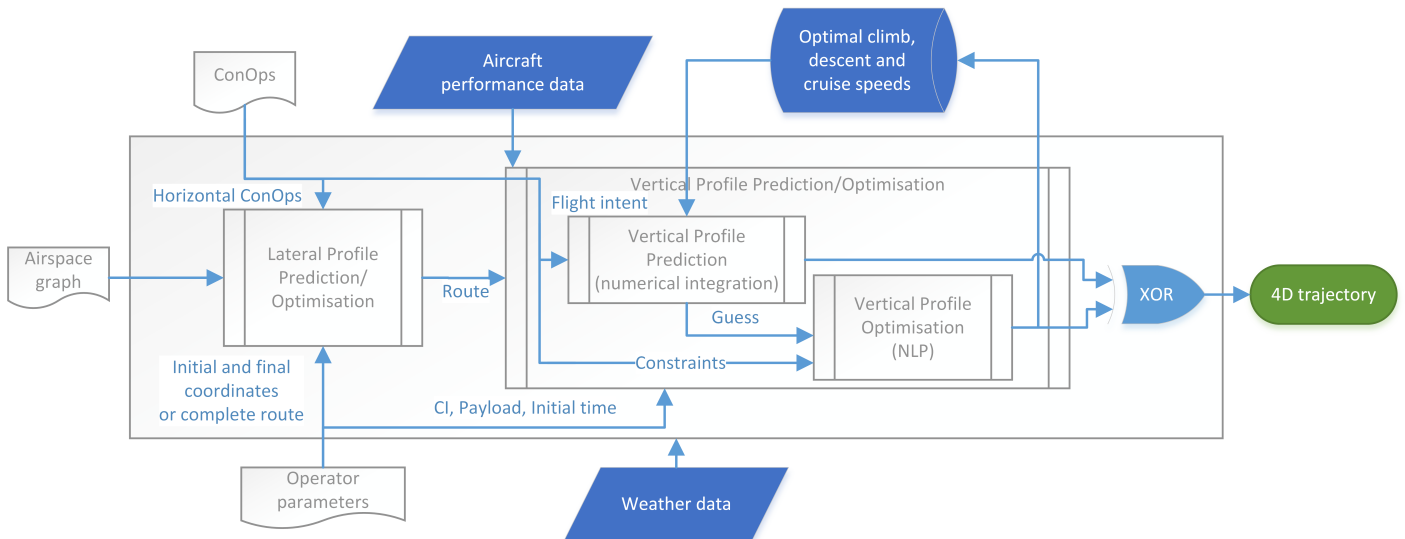


Fig. 1: DYNAMO architecture

II. DYNAMO TRAJECTORY PREDICTOR AND OPTIMISER

DYNAMO decouples the generation of the lateral and vertical profiles. The lateral profile prediction/optimisation module is in charge of generating the sequence of waypoints from origin to destination (i.e. the route). Subsequently, the vertical profile prediction/optimisation module generates the altitude and speed profiles assuming a fixed and known route. This process is depicted in Fig. 1, together with the required inputs. Section II-A describes these inputs. Then, Sections II-B and II-C present the working principle of the two main modules.

A. Input data

DYNAMO requires the following inputs to optimise/predict:

1) *Aircraft performance data*: mathematical functions describing the forces acting on the aircraft (thrust and drag) and the fuel flow. The thrust and fuel flow for the different throttle settings and the drag coefficient for the different aerodynamic configurations may rely on propulsive and aerodynamics models obtained from the Base of Aircraft Data (BADA) [11], a database generated and maintained by EUROCONTROL, in cooperation with aircraft manufacturer and operating airlines.

For trajectory prediction purposes, DYNAMO can be fed either with BADA v.3 or BADA v.4 performance models. However, several works already reported the limitations of BADA v.3 for the prediction of trajectories in the Terminal Maneuvering Area (TMA) [12]. In addition, since the drag coefficient model of BADA v.3 does not take into account the compressibility effects that occur at high Mach numbers, it is not appropriate for trajectory optimisation purposes [13]. BADA v.4 overcomes these issues by providing enhanced models for the aircraft performance functions in the various flight regimes, and by considering compressibility effects in the drag coefficient model.

A virtue of DYNAMO is that it also accepts performance data in tabular form, such as those obtained from the performance tools provided by aircraft manufacturers and/or directly

coming from flight tests. These tables contain data for the thrust, fuel flow and drag coefficient for various flight conditions.

2) *Weather data*: DYNAMO can predict/optimize aircraft trajectories using weather models of various complexity.

On the one hand, the International Standard Atmosphere (ISA) model can be considered, which defines the density, pressure and temperature magnitudes as functions of the altitude. Regarding the wind, simplified wind fields can be modelled by assuming constant wind speed and direction all along the route, or empirical wind profiles (function of the altitude only) such as the Hellmann power-law model.

On the other hand, DYNAMO can be fed with real weather data. These data must be provided in GRIdded Binary (GRIB) format, a concise data format used in meteorology to store historical and forecast weather data, composed by a collection of weather records defined at a regular grid of latitudes and longitudes for different pressure levels and time stamps.

3) *Operator parameters*: These parameters include the cost index (CI), which reflects the relative importance of the time and fuel costs; payload and flight plan. The flight plan is composed by the initial and final coordinates (or the whole sequence of waypoints for a fixed route) and the initial time.

4) *ConOps (Horizontal)*: The horizontal ConOps specify how the lateral route has to be generated. Three different variants of horizontal ConOps can be simulated with DYNAMO: fixed route, in which the route is not optimised but specified by the user through a sequence of waypoints (typically used for trajectory prediction purposes); structured route, in which the lateral route is optimised by constraining the feasible set of waypoints to those included in the ATS route network, and aircraft must fly straight between two consecutive waypoints following published airways; and free route, in which the lateral route is optimised with the possibility of routing via intermediate (published or unpublished) waypoints.

The airspace structure is provided to DYNAMO as a graph, composed by nodes and edges interconnecting them. The edges and nodes of the graph depend on the particular ConOps being simulated: when mimicking structured route operations, the nodes and edges are the waypoints and airways of the ATS route network, respectively; for free route operations, the nodes are defined at an oriented grid of latitudes and longitudes with a certain granularity (e.g. $0.1^\circ \times 0.1^\circ$), and the edges are defined such that the number of successors of each node is minimised while covering a wide range of bearing alternatives.

5) *ConOps (Vertical)*: Specify how the speed and altitude profiles have to be generated. This is accomplished by means of a XML-formatted file defining the *flight profile*, which is composed by a flexible number of flight phases. Each phase of the flight profile contains information about the aerodynamic configuration and the throttle setting, and may also include various *event* and *path* constraints. The former fix the initial and/or final conditions of the phase; the latter apply all along the phase, and represent airline operations, Air Traffic Control (ATC) restrictions and ATM procedures. A list of path constraints that could be defined in an ATM context is given in [14]. Listing 1 shows a generic XML flight profile. Table I shows the constraints that DYNAMO is able to handle.

A generic constraint in the flight profile is composed by different parameters: constraint type; nominal value; and upper and lower bounds. The constraint type indicates the function affected by the constraint. In addition, a “constant” tag can be set to “true” if the associated function is to be kept constant all along the phase. The “nominal” value parameter is used for trajectory prediction purposes, indicating which value will the function affected by the constraint take during the prediction.

B. Lateral profile prediction/optimisation module

This module receives the initial and final coordinates above the WGS-84 ellipsoid, or the complete sequence of waypoints in the case that the route were fixed. In the former case, the optimal route is computed, which minimises a realistic performance index (J_{lat}) composed by a weighted sum of the cost of time, fuel consumption and airspace route charges:

$$J_{lat} = \int_0^{s_f} \left(\underbrace{\frac{c_t}{\dot{s}(s)}}_{\text{Time}} + \underbrace{\frac{c_f f(s)}{\dot{s}(s)}}_{\text{Fuel}} + \underbrace{\frac{dc_r(s)}{ds}}_{\text{Route charges}} \right) ds \quad (1)$$

where f is the fuel flow; c_f and c_t are the unit costs of fuel and time, respectively; c_r is the cost of the route charges; s_f is the total flight distance (unknown a priori); and $CI = c_t/c_f$.

It should be noted that, even if not explicitly shown in Eq. (1), it is straightforward to minimise only ground distance.

The optimal route is computed with the well-known A* algorithm [15], using the graph representing the airspace structure. For the heuristic part, the straight distance from the current to the last node is considered, assuming an extremely heavy tail wind and the minimum route charges unit cost.

TABLE I: Types of constraints handled by DYNAMO

Variable affected	Description	Allowed in	
		Path	Event
v_{CAS}	Callibrated Airspeed (CAS)	✓	✓
\dot{v}_{CAS}	CAS acceleration/deceleration	✓	✗
v	True Airspeed (TAS)	✓	✓
M	Mach number	✓	✓
h_p	Pressure altitude	✓	✓
h	Geometric altitude	✓	✓
k	Energy Share Factor (ESF)	✓	✗
\dot{h}_p	Vertical Speed (VS)	✓	✗
\dot{h}	Geometric altitude rate	✓	✗
\dot{s}	Ground Speed (GS)	✓	✗
γ_g	Ground Flight Path Angle (FPA)	✓	✗
γ	Aerodynamic FPA	✓	✗
T	Thrust	✓	✗
n_z	Load factor	✓	✗
β	Speedbrakes	✓	✗
m	Mass	✗	✓
s	Along path distance	✗	✓
t	Time	✗	✓

Listing 1: Generic DYNAMO flight profile

```
<Profile>
  <Phase id="">
    <configuration></configuration><setting></setting>
    <event>
      <initial>
        <constraint type="" constant="">
          <upper units=""></upper>
          <lower units=""></lower>
          <nominal units=""></nominal>
        </constraint>
        ...
      </initial>
      <final>
        <constraint type="" constant="">
          ...
        </constraint>
      </final>
    </event>
    <path>
      <constraint type="" constant="">
        ...
      </constraint>
      ...
    </path>
  </Phase>
  ...
</Profile>
```

Each edge interconnecting two nodes in the airspace graph includes information about the ground distance, mean longitudinal wind and route charges. Since the altitude profile is not known a priori, the mean longitudinal wind at each edge is given for a “guess” flight level and an estimated overfly time. The fuel flow at each edge is computed by assuming the guess flight level and the optimal speed for its weather conditions.

C. Vertical profile prediction/optimisation module

Once the optimal route has been computed, this module optimises or predicts the vertical (speed and altitude) profile.

Let us divide the vertical profile into N phases. For each phase i , defined over the time period $[t_0^{(i)}, t_f^{(i)}]$, a state vector $\mathbf{x}^{(i)}(t)$, a control vector $\mathbf{u}^{(i)}(t)$ and parameter vector $\mathbf{p}^{(i)}$ (composed by variables that are not time dependent) are defined. Typically, $\mathbf{x}^{(i)} = [v, \gamma, h, s, m]$ and $\mathbf{u}^{(i)} = [T, n_z, \beta]$.

The dynamics of \mathbf{x} are expressed by the following set of Ordinary Differential Equations (ODE), considering a point-mass representation of the aircraft¹:

$$\frac{dv}{dt} = \dot{v} = \frac{T - D(v, h, m, \beta, \phi)}{m} - g \sin \gamma \quad (2a)$$

$$\frac{d\gamma}{dt} = \dot{\gamma} = \frac{g}{v} (n_z \cos \phi - \cos \gamma) \quad (2b)$$

$$\frac{dh}{dt} = \dot{h} = v \sin \gamma \quad (2c)$$

$$\frac{ds}{dt} = \dot{s} = \sqrt{v^2 \cos^2 \gamma - W_x(s, h)^2} + W_s(s, h) \quad (2d)$$

$$\frac{dm}{dt} = \dot{m} = -f(v, h, T) \quad (2e)$$

where D is the aerodynamic drag; W_x and W_s are, respectively, the cross and along path wind components; g is the local gravity acceleration; and ϕ is the bank angle.

In DYNAMO the turns at the different waypoints of the route are supposed to be flown in such a way that a constant radius is described over the horizontal Earth plane. In order to keep a constant radius, the bank angle must be continuously adjusted during the turn as long as the GS changes. Therefore, ϕ is computed as a function of the turn radius and the GS.

DYNAMO can be used either to predict or to optimise the vertical profile using Eq. (2). Next sections present the working principle of DYNAMO in these two configurations.

1) *The trajectory prediction problem:* From an initial aircraft state (\mathbf{x}_0), a trajectory prediction algorithm aims at computing future states, based on the flight intent, weather data and an aircraft performance model (without optimising).

Mathematically, the flight intent of each flight phase i could be given as a certain control vector closing the two degrees of freedom of Eq. (2), and a final event constraint. In practise, however, aircraft are not operated following specific T and γ profiles, and these controls are not known beforehand. Instead, climbs and descents are typically composed by constant Mach, CAS or ESF segments performed at maximum climb and idle thrust, respectively; while in the cruise phase aircraft typically fly at constant h_p and M . In a generic formulation, two path constraints (see Table I) close the mathematical problem:

$$h_k^{(i)}(\mathbf{x}^{(i)}(t), \mathbf{u}^{(i)}(t), \mathbf{p}^{(i)}) = 0; \quad k = 1, 2 \quad (3)$$

For instance, the first path constraint of an hypothetical phase i could enforce to fly at constant pressure altitude (i.e. $h_1^{(i)} = \dot{h}_p = 0$), while the second one could restrict the CAS to be constant (i.e. $h_2^{(i)} = \dot{v}_{CAS} = 0$). In such case, the two

¹In many applications the Eq. (2) is reduced to what is called a "gamma-command" model [9], where continuous vertical equilibrium is assumed (lift balances weight). With this simplification, Eq. (2b) is removed and γ is considered a control that can change instantaneously (i.e. $\mathbf{u}^{(i)} = [T, \gamma, \beta]$).

parameters defining the constant h_p and CAS values of that phase must be specified to perform the numerical integration.

The dynamics of \mathbf{x} (2) together with two path constraints (3) form a system of Differential Algebraic Equations (DAE). Provided that the path constraints are meaningful (i.e. they close the mathematical problem), \mathbf{u} can be explicitly determined, reducing the DAE system to an ODE system suitable for numerical integration using numerical procedures. The integration of a phase i is performed until reaching the final event constraint, which triggers the switch to the next phase.

$$e^{(i)}(\mathbf{x}^{(i)}(t_f^{(i)}), \mathbf{p}^{(i)}) = 0 \quad (4)$$

The resulting vertical profile is the output if DYNAMO is configured as a trajectory predictor. Otherwise, a multi-phase, constrained optimal control problem is formulated and solved using this profile to initialise the optimisation algorithm.

2) *The trajectory optimisation problem:* DYNAMO formulates the optimisation of the aircraft trajectory as an optimal control problem, which aims at finding the best control and parameter vectors that minimise the following cost function J_{vert} , defined over the whole time period $[t_0^{(1)}, t_f^{(N)}]$:

$$J_{vert} = \int_{t_0^{(1)}}^{t_f^{(N)}} (f(t) + CI) dt \quad (5)$$

In order to guarantee a feasible and operationally acceptable trajectory, as a result of the optimisation, several constraints must be considered. In particular the *dynamics* constraints (2).

The solution might satisfy *event* inequality constraints defined at each phase i , with $i = 1, \dots, N$:

$$e_{k,L}^{(i)} \leq e_k^{(i)}(\mathbf{x}^{(i)}(t_f^{(i)}), \mathbf{p}^{(i)}) \leq e_{k,U}^{(i)}; \quad k = 1, \dots, n_e^{(i)} \quad (6)$$

and may also include *path* inequality constraints (see Table I):

$$h_{k,L}^{(i)} \leq h_k^{(i)}(\mathbf{x}^{(i)}(t), \mathbf{u}^{(i)}(t), \mathbf{p}^{(i)}) \leq h_{k,U}^{(i)}; \quad k = 1, \dots, n_h^{(i)} \quad (7)$$

Here, $n_e^{(i)}$ and $n_h^{(i)}$ denote the number of event and path constraints of phase i , respectively.

In the previous notation, $(\cdot)_L$ and $(\cdot)_U$ are respectively the lower and upper bounds for these constraints. It should be noted that equality constraints can be defined by setting the lower bound equal to the upper bound, i.e. $(\cdot)_L = (\cdot)_U$. These bounds are specified in the "upper" and "lower" tags of the corresponding constraint in the flight profile (see Listing 1). In addition, the final event constraints of a given phase correspond to the initial event constraints of the following one.

The main difference between the trajectory prediction and optimisation problem is that for the former two path constraints and one final event constraint must be defined at each phase, and Eq. (2) is numerically integrated using fixed values for the constraints. For the latter, an unlimited number of path and event constraints may be defined at each phase; and their values are not known a priori but optimised by the solver such that Eq. (5) is minimised while satisfying the bounds.

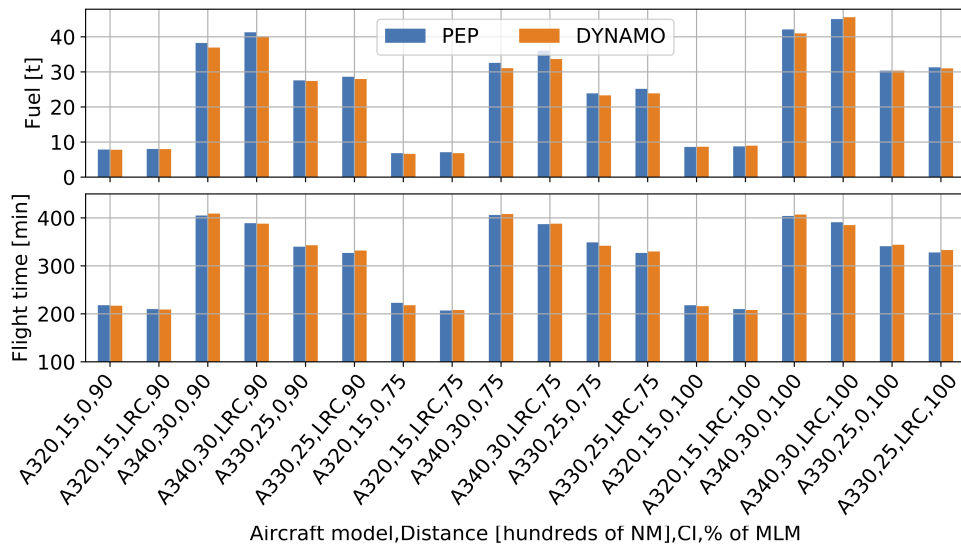


Fig. 2: Fuel and time comparison between PEP and DYNAMO

The variables, constraints and cost function are provided to the General Algebraic Modelling System (GAMS) software suite, where the continuous optimal control problem is transcribed into a finite-dimensional optimisation problem by means of direct collocation methods [16]. Then, the resulting Non-Linear Programming (NLP) optimisation problem is solved using large-scale efficient solvers (e.g. CONOPT).

These solvers are executed from a starting point with the variables of the problem initialised to some value. From this starting point, the internal algorithms aim to find a feasible (fulfilling the constraints) and optimal (minimising Eq. (5)) solution. The guess trajectory corresponds to that initially computed by numerical integration using the "nominal" values.

Unfortunately, for real-time applications or studies requiring to optimise a large set of trajectories, this method may result in unacceptable and unpredictable execution times. In addition, gradient-based optimisation methods may suffer from local minima and convergence issues difficult to trace and fix.

In order to overcome these issues, a variant of the vertical profile optimisation module has been developed. This variant is configured as a trajectory predictor, but instead of using user-defined "nominal" values for the two path constraints (3), these values are obtained from look-up tables. These look-up tables, which contain information about optimal climb and descent speed schedules and optimal cruise speeds (as a function of the aircraft mass, altitude, longitudinal wind, deviation with respect to ISA and CI), are computed off-line for each aircraft type and for a wide variety flight conditions.

This strategy considerably speeds-up the trajectory optimisation process, avoiding at the same time convergence issues, at the expense of penalising the accuracy of the obtained trajectories and reducing the flexibility to formulate constraints; namely, the impossibility to add a number of path and final event constraints different from two and one, respectively.

III. DYNAMO VALIDATION

This section shows the results of a validation exercise, in which the vertical profile of 18 trajectories computed with

DYNAMO were compared with those generated by the Airbus PEP (Performance Engineering Program) software suite for the same input parameters.

Airbus PEP is an application designed to provide flight performance engineers with the necessary tools to handle the performance aspects of flight. PEP comprises several modules, one of which produces fuel predictions for a given flight under simplified meteorological conditions, accounting also for airline cost policies and aircraft performance capabilities.

PEPs assist dispatchers in determining the fuel quantity to be carried, as long as optimal cruise level(s) and speeds, as a function of the payload, the distance and the CI. These trajectories are computed using performance data from the manufacturer and optimisation algorithms similar to those installed in the Flight Management Systems (FMS).

It should be noted that PEP does not allow real weather data as input for the optimisation of the trajectories. Due to this limitation of PEP, the trajectories have been computed in ISA conditions and without winds. Accordingly, this validation exercise is only applicable to the vertical profile optimisation module considering standard atmospheric conditions. In addition, a straight-line route from origin to destination has been assumed, and a conventional flight levels orientation and allocation scheme has been configured in the flight profile.

Results of a second validation exercise with a similar trajectory optimisation tool can be found in Ref. [17]. There, 1500+ trajectories were optimised under the same conditions in both tools, using realistic weather data, different combination of horizontal and vertical ConOps and a variety of optimisation criteria. Results successfully validated both vertical and lateral optimisation modules of DYNAMO, in realistic weather conditions, and for different horizontal and vertical ConOps.

The input parameters include the aircraft model, the landing mass, the CI and the trip distance. The set of trajectories is obtained as a result of combining different values of these input parameters. Three representative Airbus models, which are included in the PEP database, have been used for the validation

exercise: The Airbus A320-213, the Airbus A330-321 and the Airbus A340-231. For each aircraft model, the trajectories for 3 landing masses and 2 CI have been investigated. On the one hand, the following landing masses have been considered, which are expressed as a percentage of the Maximum Landing Mass (MLM): 75%, 90% and 100%. On the other hand, the trajectory that minimises fuel consumption (i.e. CI = 0 or maximum range), and that using a CI representative of Long Range (LRC) operations have been analysed. Finally, a typical trip distance has been selected for each aircraft model. These distances are 1500, 2500 and 3000 NM for the A320, A330 and A340, respectively.

The metrics for the comparison shown in Figure 2 are the differences in flight time and fuel consumption figures.

According to Fig. 2, the trajectories generated by DYNAMO and PEP are comparable in terms of flight time and fuel consumption. In most of the cases, DYNAMO reported slightly less fuel consumption. The mean absolute relative difference in fuel consumption is around 2.4%, being 6.6% the maximum absolute relative difference. Regarding the flight time, these statistical indicators are 1% and 2.2%, respectively. In addition, the optimal cruise speeds and altitude profiles reported by DYNAMO and PEP are very similar.

IV. ILLUSTRATIVE EXAMPLES

DYNAMO has been used in many different applications and assessments. This section highlights three representative examples where DYNAMO has been used to optimise trajectories. More examples can be found in [9], where DYNAMO was configured to generate optimal CCC and conventional trajectories to assess the benefits of suppressing vertical constraints in the flight plan; in [18], [10], where it is coupled with a self-separation algorithm; in [19], [20] as centrepiece for future sequencing and merging concepts in dense TMAs; or in [21], where it was used as part of an advanced demand and capacity balance algorithm in the context of trajectory based operations.

A. Trajectory optimisation for flight planning purposes

A clear application of DYNAMO is the planning of trajectories by aircraft operators. Recalling Eq. (1), DYNAMO can be configured to generate trajectories minimising a cost function composed by a weighted sum of fuel, time and route charges costs. These weights would be selected at dispatch level in order to reflect the business strategy of the operator.

Figure 3 presents an illustrative example for a given origin-destination airports, aircraft model and route structure; but changing the optimisation cost function, while considering realistic weather conditions. This Figure also shows the unit route charges cost associated to each Flight Information Region (FIR). The orange line shows the route minimising only ground distance (but still constrained to published ATS route structure); the blue line represents the route minimising only fuel consumption, which takes advantage of the favourable weather conditions to reduce fuel burnt even if flying more ground distance; and the green line is the optimal route minimising the total cost. It can be seen how this last route

tries to avoid the Spanish airspace, which is more expensive in terms of route charges than the Portuguese airspace.

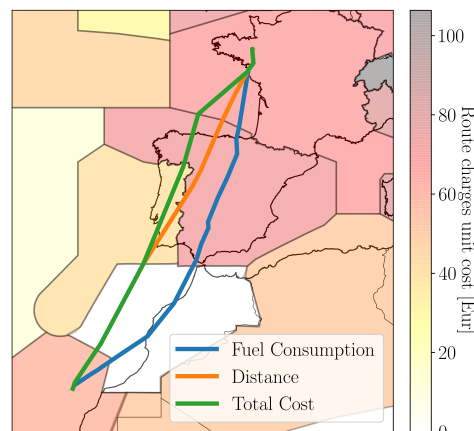


Fig. 3: Example of optimal routes

Figure 4 compares the optimal vertical profile (altitude and speed) of another flight set, on one hand, to minimise the flight time; and on the other hand, to minimise the ground distance. As seen in Fig. 4, when optimising for time the ground distance increases, looking for favourable winds. This difference may lead to distinct vertical profiles, with a noticeable shift of the location where the step climb is initiated.

B. Massive optimisation of trajectories for ATM analytics

In the APACHE Project (a SESAR Exploratory Research project [17]) DYNAMO was used to generate realistic traffic scenarios based on real or future traffic demand (flight plans) for various vertical and horizontal ConOps, using realistic aircraft performance models (taken from BADA v4.1) and weather data (taken from the Global Forecast System).

In APACHE, more than one million trajectories were optimised. Given this large number of trajectories, DYNAMO was configured to use look-up tables for the optimal climb, descent and cruise speed schedules, aiming at speeding-up the computation time. The trajectories were computed in a distributed manner using a software and hardware architecture taking advantage of high performance computing concepts [7].

Regarding the lateral ConOps, both scenarios with all the flights operating in a futuristic free route airspace and following the current ATS route network have been simulated.

Figure 5 shows two example optimal routes: one constrained to follow published ATS routes, while the other assumes an hypothetical scenario with free route operations from origin to destination. The wind barbs indicate the wind filed to a pressure altitude of 200 hPa (around FL380). As expected, in a free route context flights take more direct routes. In addition, this gives more freedom to follow favourable winds and maximise the ground speed.

Finally, Figure 6 shows optimal trajectories (for the ATS structured route scenario) crossing the French airspace in a typical day of operations.

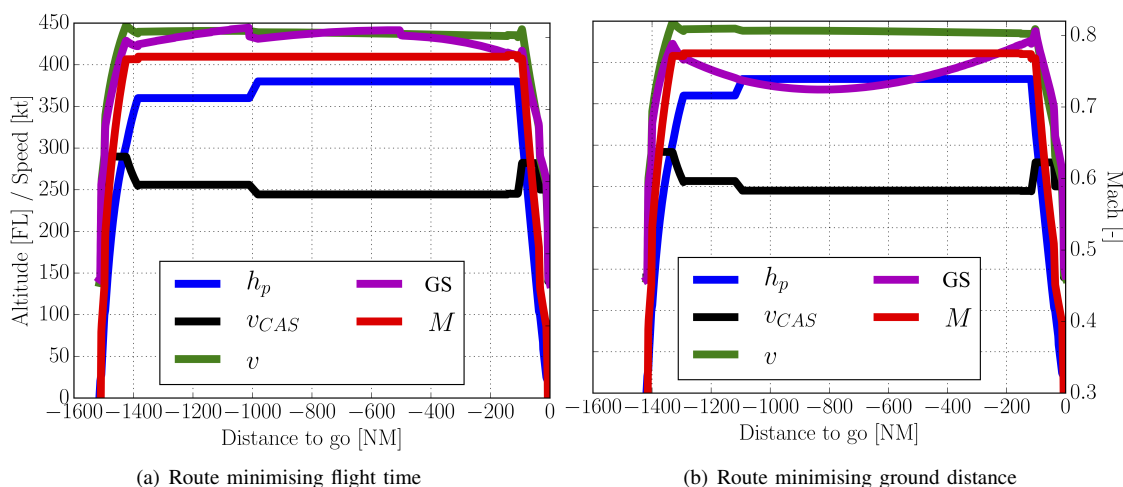


Fig. 4: Example of optimal vertical profiles

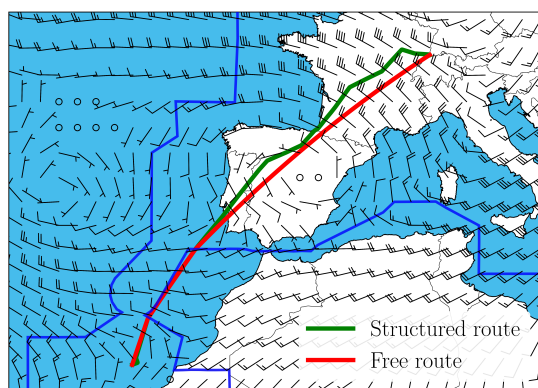


Fig. 5: Comparison of free and structured route trajectories



Fig. 6: Optimal trajectories for the structured route scenario

C. On-board, real-time optimisation for enhanced CDO

New ATM paradigms aim to remove open-loop air traffic control (ATC) vectors (i.e. tactical path stretching) by efficiently implementing 4D trajectories. In this context, ATC could sequence and merge arrival traffic by assigning to each aircraft time constraints at one or several metering fixes, without the need to modify their planned arrival route.

In the FASTOP Project (a Clean Sky funded project), DYNAMO was adapted to optimise the vertical profile during Continuous Descent Operations (CDO), in order to minimise fuel consumption and speed-brake usage, while satisfying ATC time constraints and taking into account realistic standard operational procedures constraining this profile [8].

In this new CDO concept, called Time and Energy Managed Operations (TEMO)², energy and time deviations (with respect to the active optimal plan) are continuously monitored during the execution of the descent by the guidance system. Whenever these errors reach a pre-defined threshold, a new optimisation is triggered in real-time in order to generate a new trajectory starting from the current aircraft position [22].

In contrast with the previous examples, here DYNAMO was embedded on-board into a research FMS and the optimisation was done by solving the optimal control problem with NLP algorithms, which gives more flexibility to define complex flight profiles, with numerous phases and a wide diversity of operational constraints. Moreover, instead of using BADA v4, aircraft performance data obtained from flight tests were used.

It should be noted that besides the optimal vertical profile, DYNAMO also computes the right locations where flaps/slats and landing gear shall be deployed. The objective of TEMO is to achieve high time predictability and therefore it is important to ask the pilot to use these devices at the right moment.

In 2015, after FASTOP Project but still within the Clean Sky programme, the Netherlands Aerospace Centre (NLR) in cooperation with Delft University of Technology (TUD) and with the support of the CONCORDE Project consortium, executed some flight trials with a Cessna Citation II research aircraft to further test the TEMO concept [22], [23].

Figure 7 shows the navigation display used in these experiments, where an optimal trajectory generated by DYNAMO can be seen. Note that even if the route was fixed beforehand (only the vertical profile is optimised), turns were accurately modelled by the planning (DYNAMO) and guidance algorithms. Moreover, the display also shows the exact locations, as computed by DYNAMO, where the different flaps/slats configurations and the landing gear must be deployed.

Finally, Figure 8 shows DYNAMO running in the research FMS of the Cessna Citation II aircraft during one of the descents of the flight-test campaign.

²<https://youtu.be/9u9nYR5mR4E>



Fig. 7: Optimised trajectory by DYNAMO as seen in the Navigation Display



Fig. 8: DYNAMO running in a research FMS

V. CONCLUSIONS

The DYNAMic Optimiser (DYNAMO) optimisation framework presented herein provides fast results for trajectory optimisation and prediction problems of different kind and complexity. Together with a simulation environment, these serve the purpose of evaluating current Air Traffic Management (ATM) paradigm structure and procedures, along with proposing enhancements for a more sustainable future. In future work, effort will be devoted to couple the lateral route and vertical profile optimisation by means of an iterative algorithm. In addition, potential parallelisable regions in the DYNAMO routines will be identified and fully exploited. Last but not least, it is also envisaged to make DYNAMO publicly available through a web service application which, given the user's inputs (weather, flight profile, aircraft performance, etc.) in a web interface, will provide the optimal trajectory.

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