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Algorithms for Automatic Elaboration of Optimized Trajectories for Continuous Descent Operations

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Abstract: To reduce the effects of aircraft noise, fuel use and related pollutant atmospheric emissions, due to conventional step-down procedures for approach and landing, designed curved and continuous descent approach trajectories can be adopted in order to provide suitably optimized vertical profiles by combining flexible lateral paths and continuous descent operations such that level flight segments can be completely eliminated. This paper describes a methodology for the automatic generation of efficient Curved and Continuous Descent Approach (CCDA) trajectories to reduce the aircraft fuel consumption during the approach phase. Furthermore, the proposed method takes into account the airport and external environmental constraints by providing the obstacles mapping from aeronautical charts georeferencing processes and suitable DSMs and DTMs. This allows to automatically generate a modified set of trajectories that optimizes the track distance within a tolerable range. The Italian Aerospace Research Center (CIRA) has developed this study within the framework of the Efficient Air Transport System (EATS) project. The identification of all influencing factors in TMA has been here provided for a specified airport and related Aerodrome Traffic Zone and Control Zones in collaboration with the University of the Study of Naples “Parthenope”. Applications and simulations results of the proposed methodology have been reported and discussed.

Keywords: Continuous descent operation, Fuel efficiency, 3D obstacles mapping, Terminal manoeuvring area.

Nomenclature

AGL = Above Ground Level
ANSP = Air Navigation Service Provider
ATC = Air Traffic Control
ATM = Air Traffic Management
CDA = Continuous Descent Approach
D = Aerodynamic drag [N]
d/dt = time derivative [s^{-1}]
FAF = Final Approach Fix
g = gravitational acceleration [9.81 m/s^2]
h = altitude [m]
IAF = Initial Approach Fix
ISA = International Standard Atmosphere
m = aircraft mass [kg]
k_T = ISA temperature gradient with respect to altitude, below the tropopause [K/m]
ρ_0 = air density at sea level [kg/m^3]
R = real gas constant for air [m^2/Ks^2]
T = Thrust acting parallel to the aircraft velocity vector [Newton]
TOD = Top of Descent

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TMA = Terminal Maneuvering Area
V_{TAS} = true airspeed [m/s]

I. INTRODUCTION

The aircraft noise, fuel use and related pollutant atmospheric emissions can impact on populated areas near to airports, leading to restrictions applied to aircraft and ATC operations. One of the innovative concepts introduced in the last years reducing noise and pollutant emissions is a direct descent at idle or near-idle thrust, beginning at entry to the terminal control area from cruise until touchdown. This technique is generally referred to the Continuous Descent Operation (CDO) concept.

ICAO defines CDO "*an aircraft operating technique aided by appropriate airspace and procedure design and appropriate ATC clearances enabling the execution of a flight profile optimized to the operating capability of the aircraft, with low engine thrust settings and, where possible, a low drag configuration, thereby reducing fuel burn and emissions during descent. The optimum vertical profile takes the form of a continuously descending path, with a minimum of level flight segments only as needed to decelerate and configure the aircraft or to establish on a landing guidance system (e.g. ILS).*" [1]. The generic term CDO is addressed to different techniques like Continuous Descent Approaches (CDA), Optimized Profile Descents, Tailored Arrivals, Increased Glide Slope, depending on different operation based on specific local airspace requirements and constraints.

Generally, the continuous descent procedure is a technique that simplifies the non-precision final approach with precision curved approach and vertical guidance procedures, resulting in a continuous vertical path calculated by on-board equipment or manually based on a required rate of descent without level flight segments. Fig. 1 reports the differences between a continuous descent approach and a step-down trajectory.

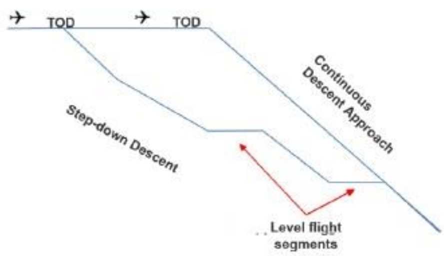

Fig. 1. Continuous descent approach compared to conventional descent profile.

Today's STAR procedures cover the phase from the Top-Of-Descent (TOD) until the runway. The initial point is defined as Initial Approach Fix IAF and the transitions are addressed to description of routes by the waypoints. Then, the aircraft can intercept the Instrument Approach Point IAP or can be vectored by Air Traffic Controllers ATCo. In the final approach, the alignment and descent for landing are made. The conventional technique for vertical path control is a step-down descent that shall start at not below the minimum step-down fix altitude. As an alternative, the continuous descent allows the aircraft to fly higher for a long time with respect to the conventional approach, descending continuously from the lower level of holding and avoiding any level flight segment before to intercept the glide path (typically defined to 3.5 degrees for the ILS).

As defined in the CDA Implementation Guidance by EUROCONTROL [2], CDA implementation is achieved through collaboration between operational stakeholders, in order to satisfy functional and non-functional requirements. Particularly, the Air Traffic Controls (ATCs) could have some difficulty predicting an aircraft descent trajectory at idle trust as the CDAs could differ with respect to wind, temperature, and aircraft characteristics (i.e., adopted flight management system FMS, airframe, weight, engines and speed). Furthermore, the radar vectoring and vertical profile management can influence the arrival phase increasing the ATCs workload. Hence, the implementation of a curved and continuous vertical profile is expected to eliminate the level flight segments as far as possible. This is achievable through applying the Rules of the Air [3], and considering the air traffic control procedures based on the advanced flight transitions over curved trajectories directly connected to satellite systems for the precision final approach such as the Performance-Based Navigation PBN [4].

This paper provides a methodology for generating vertical profiles for a generic aircraft and validate a system enabling to compute curved and continuous trajectories along more optimized approach and landing profiles in terms of aircraft fuel consumption, in TMA environment typically rich of obstacles. Specifically, such techniques are implemented to compere the CDA vertical profile with the conventional techniques of descent. Furthermore, the proposed algorithms are designed to generate curved and continuous trajectories. These functions take into account the dynamic restrictions of the considered aircraft and external space constraints in TMA, in order to avoid automatically any obstacles along the final phases of aircraft route, and to select the optimal trajectory in terms of reduction of fuel consumption.

This study is part of the EATS – Efficient Air Transport System Project, an Italian funded project of CIRA – Italian Aerospace Research Center, started in September 2015, developed within activities of the Air Transport Sustainability Department. The Project aimed at extending the CIRA systems for traffic avoidance and collision avoidance, integrating the new airborne sequencing and merging systems, and developing the algorithms for the efficient curved and continuous approach and operations.

The following section presents an overview of the Continuous Descent Approach CDA concept. After that, the section “Methodology” describes the proposed curved and continuous trajectories generation system and the setup for fast-time simulations. In addition, this section includes the mathematical model to compute the trajectories and the fuel consumption. The assumptions, the implemented scenario, the metrics for validation and the results of the simulations are presented, finally in the section named “Applications” followed by the “Conclusions” section.

II. BACKGROUND

Although the hasty increase of aviation demand is generating many positive aspects like jobs and faster world connections, it introduces more issues due to pollution, noise and climate change. NEXGEN and Europe’s SESAR Programme aim at strategically remodeling and adjusting the arrival procedures in a more efficient way increasing capacity, productivity and safety and reducing the environmental impact in proximity of airport.

Since there are no specific guidelines for designing CDAs, the CDA implementations differ with respect to the start altitude and speed as stated from many different researches. Furthermore, to evaluate and demonstrate the benefits of CDA procedure, several flight trials have been conducted at several airports in the US and the EU. For example, in U.S., a program known as Partnership for AIR Transportation Noise and Emission Reduction (PARTNER), also designed detailed CDA models, and conducted field tests at Louisville International Airport (KY, U.S.) and at Los Angeles International Airport [5,6]. For the flight trials at Louisville International airport [5], CDAs started at 11000 ft. The trial was conducted during late night landing operations by UPS aircraft at Louisville International Airport (KSDF) in 2004. This flight trial, leveraging the capability of the FMS, proved the stated benefits of a CDA procedure [5]. European Commission initiated a program, known as Optimized Procedures and Techniques for Improvement of Approach and Landing (OPTIMAL) in 2004, in which CDA profiles and associated descent procedures are established [7]. Two major CDA trials were conducted at the Schiphol Airport, Amsterdam, Netherland, in 2006, and at the Heathrow Airport in 2007, [7]. The aim was to define and validate innovative procedures for the approach and landing phases of aircraft and rotorcraft. The objective was to increase airport capacity and to reduce environmental impacts (noise and carbon footprints) while maintaining or even improving operational safety. In the EU co-funded Project within the Sixth Framework Programme (FP6), the Project namely Environmentally Responsible Air Transport (ERAT) was defined to select the terminal airspaces above the airports Stockholm Arlanda and London Heathrow as

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reference site to focus the development of concepts aimed at improving environmental performance in terms of noise, fuel burn and emissions, [8]. The objective was to develop and validate the CONOPSs for the extended terminal airspace (eTMA) of a medium and a high density traffic airport, in such way that the environmental impact of air traffic in 2015 is significantly reduced while maintaining safety levels and airport and airspace capacity. Other researches continued to propose alternatives to reduce noise levels around airports based on previous experiences. For instance, the Project named Study of Optimisation procedures for Decreasing the Impact of Noise around airports (SOURDINE) aimed at defining new procedures for selected airports (Schiphol, Madrid and Napoli) in order to evaluate more predictable continuous descent operations, [9,10].

Even if this technique is preferred to the conventional descent, as it requires less engine thrust and consequently less emissions and acoustic impacts, the CDA procedure is influenced by the capacity of air traffic controllers and air traffic control systems, common speed constraints, altitude and separation, especially for high traffic areas. Many research project investigated on implementing of an appropriate arrival flow management in order to support the implementation of CDAs simplifying controller tasks, reducing communications and workload, and providing a better trajectory prediction, allowing for improved flight efficiency. The EUROCONTROL Experimental Centre (EEC) developed the Point Merge (PM) as an innovative technique designed to improve and harmonise arrival operations in terminal airspace with a pan-European perspective [11]. PM is designed to work without radar vectoring, and to enable, even under high traffic load, extensive use of lateral guidance by the FMS and CDA. EEC presented the main findings regarding more complex environments and advanced continuous descent [12].

III. PROPOSED METHODOLOGY

The proposed methodology aims at generating Curved and Continuous Descent Approach trajectories CCDA and comparing these different continuous vertical profiles to the conventional step-down descent profiles from predefined standard routes, and continuous profiles based-on P-RNAV waypoints.

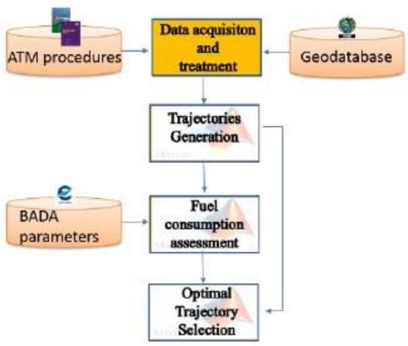

Fig. 2. Continuous descent approach compared to conventional descent profile.

Fig. 2 shows the high-level concept of the CCDA system. Particularly, the main inputs necessary for generating the trajectories and calculating the aircraft fuel consumption include also the assigned conditions assumed for this study. Once the data have been elaborated the generation of CDAs at different path angle, Optimized Profile Descent, Increased Glide Slope is done. Then, the fuel consumption is calculated for each generated trajectory, and the optimal path reducing the fuel burn is chosen. The trajectories generation algorithm allows re-calculating each trajectory to avoid a potential collision with the obstacles and restrictions related to the constraints of air navigation and produces. The CCDA trajectory corresponding to the best reduction of fuel consumption with respect to the standard arrival route is reported as final output of the CCDA system. The core process of the proposed method is the tools system for generating the trajectories developed in Matlab®. Within the Italian funded project, namely Efficient Air Transport System (EATS), which is carried out by the Italian Aerospace Research Center (CIRA), a study on the concept of CDA

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and related implementation high-level requirements and performance metrics was conducted [13]. The intent is here to report the advanced outcomes of the EATS project aiming at automatic generating of an efficient CDA trajectories system to reduce the aircraft fuel consumption during the airport approach phase. The following sub-sections provide a description of these modules, related input parameters, and the mathematical analysis of the models.

Data Acquisition and Treatment

This module takes into account the inputs from both ATM operations domain and geomatics structures derived from Geodatabase. Particularly, it aims at creating the scenario territorial framework and the thematic obstacles mapping. The ATM scenarios include the standard arrival procedures (STARs) and P-RNAV navigation published on Aeronautical Information Circular (AIC), considering the restrictions such as speed and minimum distance from obstacles. The obstacles to the navigation includes the orographic obstacles and buildings, and the restriction zones of the considered airspace. The image processing and space analysis has been done in ESRI ArcGIS environment. The mapping of the obstacles affecting the navigation depends on the scenario and the final required precision. A high-level geometric resolution is necessary around airports due to the lower flying altitudes of aircraft. To create the territorial framework the digital aeronautical chart of the considered zone are acquired and georeferenced. The zone is limited to the generated reference trajectory in order to identify only the obstacles that potentially affect the trajectories. The acquisition and the mosaicking of suitable Digital Surface Models (DSMs) and Digital Terrain Models (DTMs) allow identifying the obstacles (buildings and terrain elements). Once obstacles have been classified, a 3D buffer is created to establish the minimum distance that an aircraft has to maintain during the flight for the obstacle clearance. Fig. 3 provides an overall idea of classified buildings that are potentially dangerous in the considered airport area.

Fig. 3. Obstacles classification processing.

Subsequently, the GIS data are addressed to Matlab® software for generating trajectories and calculating related fuel consumptions.

Trajectories Generation

The trajectories generation module represents the core part of the system. Even if the tools can be applied to the whole generic trajectory, in this study only the elaborated trajectories from top of descent are described in order to demonstrate the benefit of the continuous descent path in the approach and landing phases. The scope is to generate reference trajectory and related curved and continuous descent paths through specific functionalities based on inputs and constraints parameters (as for instance, speed, altitude, obstacles, terrain profiles, etc.). The trajectories generation algorithm is defined by four main steps as shown in the Fig. 4.

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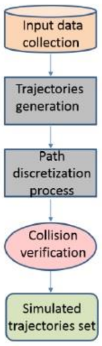

Fig. 4. Trajectories generation model flowchart.

Based on acquired and elaborated data from the previous module, this sub-system implements the first simulated trajectory that is the reference conventional descent based on step-down technique intercepting the glide path of ILS systems (typically of 3.5 degrees).
Here a set of fly-by waypoint and recommended navaids are fixed. Once the glide path angle for the reference trajectory has been fixed, a set of different CDA techniques and related calculated TODs and fixes are automatically generated and compared to step-down descent path. The glide path angle is one of the most important differences between stepdown descent and continuous descent because the angle value is zero along the level flight segments in a conventional descent path. Different curved and continuous trajectories result from variating of glide path angle. Once trajectories have been generated, the potential collisions with obstacles are investigated. In case of collision, the proposed model performs automatically corrective maneuvers identifying the interceptions between plane containing the trajectory and the obstacles buffer and circumnavigating the obstacle with the minimum path. The new trajectory is iteratively checked to identify other potential collisions. The output is a set of simulated trajectories structurally suitable to be assessed in terms of fuel consumption.
The main four steps have been developed in Matlab® and are following discussed in more detail.
The first step takes into account inputs from both ATM operations domain and geomatics structures derived from Geodatabase module (Fig. 5).

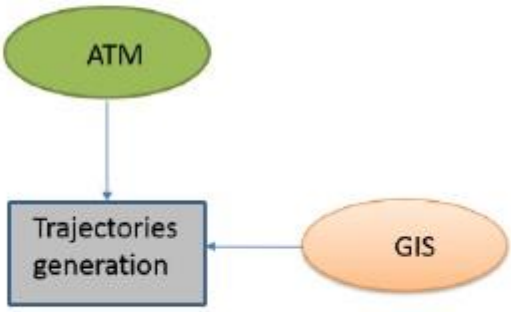

Fig. 5. First step for trajectories generation algorithm: input data collection.

Particularly, the ATM reference scenario includes standard arrival procedures (STARs) and restrictions like speed and minimum distance from obstacles. To identify and classify the obstacles, the digital surface models are processed through ESRI ArcGIS software to obtain obstacles georeferenced mapping with a high geometric resolution due to such a sensitive zone as the airport.

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Once the glide path angle for the reference trajectory has been fixed, and all mentioned inputs have been structured in a suitable format, the second step of the proposed tool is to generate the reference trajectory and a set of different CDAs (i.e., with fixed glide path, with optimized profile, etc.) (Fig. 6).

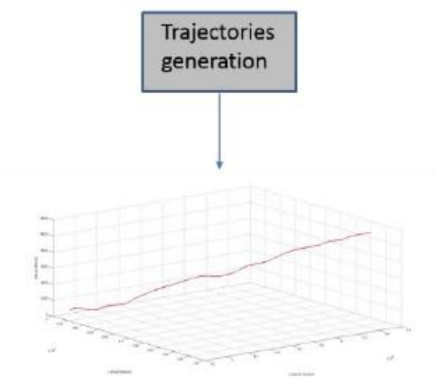

Fig. 6. Second step for trajectories generation algorithm: trajectories generation.

The trajectories generation is based on known waypoint and the use of interpolation techniques. Many consolidated study and research activities investigated on interpolated methods and related issues [14]. From a mathematical point of view, cubic interpolation technics are usually adopted for aircraft trajectory generation in TMA in order to insure a continuous trajectory curvature [15]. The analysis of the benefits and issues for different interpolation technics is out-of-scope of the paper. Given a dataset of (n+1) points, it is possible to interpolate them by a polynomial of degree n, defined as p_n that represents the curve of a spline constrained to interpolate those given points. For the planimetric and altimetric interpolations, a generic polynomial p_n of order n can be written in the following canonic formula (Equation 1 - 4):

$$\mathrm{p}_n = f(x) = \sum_{i=0}^{n} a_i x^i \qquad (1)$$

with coefficients a_i. The conditions for a polynomial interpolation expressed in the canonical basis are:

$$\sum_{i=0}^{n} a_i x_j^i = y_i \qquad (2)$$

The planimetric interpolation adopted here is based on the piecewise cubic Hermite interpolating polynomial. The interpolating function uses the known coordinates (x,y) of the STARs/P-RNAV waypoints for a selected airport, and the Euclidean distance between two consecutive waypoints P=(p_x, p_y,…,p_k) and O=(o_x, o_y,…, o_k) in the n-dimensional space, as expressed in the formula below:

$$\sqrt[2]{\sum_{k=1}^{n} \left(p_k - o_k\right)^2} \qquad (3)$$

The interval of the trajectories considered in this paper are the paths of the aircraft flying in the arrival phase. This interval is divided into regular discretised sub-interval in order to compare the fuel burn along each segment of trajectory.

The linear polynomial formula is built for the altimetric interpolation in order to achieve a direct descent path. The coordinate z_i for each point of coordinates (x_i, y_i) is given by the following formula:

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$$z_i = z_0 + (d_t - d) \times \tan(\gamma) \quad (4)$$

Where,

z_0 is the z coordinate of the origin point Po, taken as a reference (in example the track or determined the trajectory waypoints);
z_i it is the z coordinate of the point of the discretized trajectory;
dt is the total planimetric Euclidean distance between the initial point and the reference point of the trajectory;
di is the Euclidean distance between the initial partial planimetric point and the point Pi of the trajectory of the coordinates (xi, yi) for which the altitude is unknown;
γ is the glide path angle.
Through the third step, the system initiates a process of the path discretization.

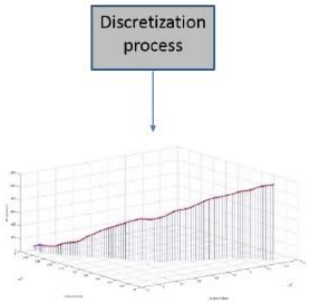

Fig. 7. Third step for trajectories generation algorithm: path discretization process.

Specifically, the reference trajectory is discretized by points in order to approximate it through a set of infinitesimal straight-lined segments. The curved and continuous trajectories are discretized along a same number of interval infinitesimal segments in order to compare the results from environmental assessment correctly for all proposed trajectories system (Fig. 7).
Once trajectories have been generated, the fourth step investigates potential collisions with obstacles (Fig. 8).

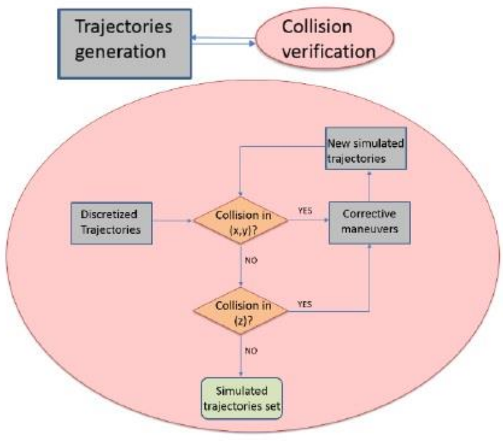

Fig. 8. Fourth step for trajectories generation algorithm: collision verification.

This analysis is performed separately in the bi-dimension and in three-dimension space for each single identified obstacle.

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From a 2D perspective, the condition to be satisfied is that the generated trajectory shall not intercept the set of the obstacles polygons plus the minimum lateral separation. Considered that both the reference and CCDA trajectories are discretized into sets of straight infinitesimal linear segments; considered that a closed oriented segmented line delimits the obstacle polygon, the problem is to identify the points of intersection between two straight lines R and S, that is, to solve a system of linear equations in Equation 5 :

$$(R) y_r = m_r x + q_r$$
$$(S) y_s = m_s x + q_s \qquad (5)$$

where q is the term known and m is the angular coefficient of the straight line.

From 3D viewpoint, the necessary condition is that the altitude of trajectory shall be major or equal to height of obstacles polygons plus the minimum vertical separation defined as the total obstacles buffer (Equation 6):

$$z_{i\_trajectory} \geq z_{altitude\_obstacle} + z_{minimum\_vertical\_separation} \qquad (6)$$

If the trajectory does not satisfy the above conditions, a corrective maneuver is necessary in order to avoid the potential conflict. The mathematical problem is firstly to identify the points surrounding the obstacles (that are the points of intersection between the inclined plane containing the trajectory and the total obstacles buffer) and then, to identify the points avoiding the obstacle and thus the potential applicable paths to which those points belong. The path generated, which minimizes the following distance, represents the corrective maneuver to be applied (Equation 7):

$$d = \sum_{i=1}^{n-1} \sqrt[2]{\sum_{k=1}^{3} (p_k^{i+1} - p_k^i)^2} \qquad (7)$$

Where:

d is the total path of the generic corrective trajectory;
n is the total number of points in the trajectory;
k identifies the (x, y, z) components for each P point of the trajectory;
i identifies which P point belonging the trajectory is considered;
P_{ki} determines the k-th coordinate of the i-th point belonging the trajectory.
In case of collision, the proposed model performs automatically corrective maneuvers identifying the interceptions between plane containing the trajectory and the obstacles buffer and circumnavigating the obstacle with the minimum path. The new trajectory is iteratively checked to identify other potential collisions. The algorithm developed in this module provides the final trajectory in a suitable form in order to be evaluated in terms of flown distance, and fuel assessment.

Fuel Consumption Assessment

This section describes the fuel assessment module starting from a detailed mathematical analysis for the fuel consumption.

The fuel consumption is influenced by different factors. The following section outlines equations derived by using flight dynamics and Base of Aircraft and Data (BADA) Total Energy Model (TEM), [16].

The Total-Energy Model, [16], equates the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy, that is (Equation 8):

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$$(T-D)V_{TAS} = mg\frac{\mathrm{dh}}{\mathrm{dt}} + mV_{TAS}\frac{dV_{TAS}}{dt} \qquad (8)$$

Below the tropopause, the air density, ρ, in kg/m3 is calculated as function of temperature as follows (Equation 9):

$$\rho = \rho_0 \left[\frac{T}{T_0}\right]^{\frac{g}{K_T R}1} \qquad (9)$$

Where:

$$-\frac{g}{K_T R} - 1 \approx 4.25864$$

with:
$R = 287.04\ m^2/Ks^2$
$g = 9.81\ m/s^2$
$k_T = -0.0065$ °K/m
$\rho_0 = (\rho_0)ISA\ (T_0)ISA\ /\ T_0$
(ρ_0)ISA is the standard atmosphere air density at sea level. $(\rho_0)ISA = 1.225\ kg/m^3$

The parameters (variables and constants) contributing to the fuel consumption formulation f are reported below. More details about the aircraft performance modelling are founded into BADA Manual [16].
For the jet and turboprop engines, the Thrust Specific Fuel Consumption η [kg/(min·kN)], is specified as a function of the true airspeed, V_{TAS} [kt] (Equations 10-12):

$$\eta = C_{f1}\left(1+\frac{V_{TAS}}{c_{f2}}\right) jet$$

$$\eta = C_{f1}\left(1-\frac{V_{TAS}}{c_{f2}}\right)\times\left(\frac{V_{TAS}}{1000}\right) turboprop \qquad (10)$$

The nominal fuel flow, fnom [kg/min] for both jet and turboprop, can then be calculated using the thrust, T:

$$f_{nom} = \eta \times T \qquad (11)$$

The minimum fuel flow fmin [kg/s], corresponding to idle thrust descent conditions for both jet and turboprop engines, is modelled as a function of the altitude h [ft]:

$$f_{\min} = k_3 c_{f3}\left(1-\frac{h}{c_{f4}}\right) \qquad (12)$$

Where:

C_{f1} is expressed in kg/(min·kN) for jet kg/(min·kN·knot) for turboprop, and kg/min for piston; it represents the first thrust specific fuel consumption coefficient.
C_{f2} is expressed in knots; it is the second thrust specific fuel consumption coefficient.
C_{f3} is expressed in kg/min; it is the first descent fuel flow coefficient.
C_{f4} is expressed in ft; it represents the second descent fuel flow.
All above coefficients are provided from BADA database [16].

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The cruise fuel flow, f_{cr} [kg/min], is calculated similar to nominal fuel flow using the thrust specific fuel consumption η, the thrust T, but also a cruise fuel flow factor, C_{fcr}. For the moment the cruise fuel flow correction factor has been established for a number of aircraft types whenever the reference data for cruise fuel consumption is available. This factor has been set to 1 (one) for all the other aircraft models.

It is importance to note that for both jet and turboprop engines, the idle thrust part of the descent stops when the aircraft switches to approach and landing configuration, at which point thrust is generally increased. Hence, the calculation of fuel flow during approach and landing phases shall be based on the nominal fuel flow.

Assuming that the geopotential pressure altitude H_p is equal to geodetic altitude h, and the true airspeed V_{TAS} is equal to ground speed v (that is ISA and no wind condition), it is possible divide the Eq. (8) by speed v on both side obtaining (Equation 13):

$$\frac{(T-D)V_{TAS}}{v} = \frac{mg\frac{dh}{dt}}{v} + \frac{mV_{TAS}\frac{dV_{TAS}}{dt}}{v} \qquad (13)$$

with v= V_{TAS}, H_p=h

Eliminating the time derivatives in Eq. (11) and introducing the term of path angle γ, the thrust can be written as (Equation 14):

$$T = mg\sin\gamma + m\frac{dv}{ds}v + D \qquad (14)$$

The aerodynamic drag D depends on the drag coefficient C_D that is expressed as a function of C_{D0} and the lift C_L as reported below (Equation 15):

$$C_D = C_{D0} + C_{D2}.(C_L)^2$$
$$CL = \frac{2mg}{\rho V_{TAS}{}^2 S\cos\varphi} \qquad (15)$$

C_{D0} is parasitic drag coefficient, and C_{D2} is the induced drag coefficient from BADA [16].
The lift coefficient, C_L, is determined assuming that the flight path angle is zero. However, a correction for a bank angle φ is made. For each phases (approach, cruise and landing configuration) a different flap setting is used. The drag D is defined as (Equation 16):

$$D = \frac{C_D \rho V_{TAS}{}^2 S}{2} \qquad (16)$$

Replacing C_L, C_{D0} and C_{D2} into (16), and considering a small bank angle $\cos\varphi \approx 1$, the aerodynamic drag can be written as (Equation 17):

$$D = \frac{C_{D0}\rho V_{TAS}{}^2}{2} + \frac{2C_{D2}m^2g^2}{\rho V_{TAS}{}^2 S} \qquad (17)$$

This formula demonstrates that the aerodynamic drag is nonlinear. At high values of speed, the drag decreases, and at low speed range it increases. Low speed leads to large lift CL and higher drag D, resulting into an increased operating time.
The definition of nominal fuel flow (11) can be written substituting the Eq. (10) for jet, Eq. (14), and Eq. (17), and assuming that the geopotential pressure altitude Hp is equal to geodetic altitude h, and the true airspeed VTAS is equal to ground speed v. It will represent the fuel flow rate fr (Equation 18):

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$$fr = cf1\left(1+\frac{v}{cf2}\right)\times\left(mg\sin\gamma + m\frac{dv}{ds}v + \frac{C_{D0}\rho S v^2}{2} + \frac{2C_{D2}m^2g^2}{\rho v^2 S}\right) \quad (18)$$

Collecting in bracket the terms multiplied per the same v value, the fuel flow rate is (Equation 19):

$$fr = \left(\frac{c_{f1}}{c_{f2}}\frac{C_{D0}\rho S}{2}\right)v^3 + \left(\frac{c_{f1}C_{D0}\rho S}{2} + \frac{c_{f1}}{c_{f2}}m\frac{dv}{ds}\right)v^2 + \left(c_{f1}m\frac{dv}{ds} + \frac{c_{f1}}{c_{f2}}mg\sin\gamma\right)\gamma + C_{f1}mg\sin\gamma + \left(\frac{C_{f1}}{C_{f2}}\frac{2C_{D2}m^2g^2}{\rho S}\right)\frac{1}{v} + \left(C_{f1}\frac{2C_{D2}m^2g^2}{\rho S}\right)\frac{1}{v^2}$$
(19)

That is (Equation 20):

$$fr = B1v^3 + (B2 + B3\frac{dv}{ds})v^2 + (B4\frac{dv}{ds} + B5)v + B6 + B7\frac{1}{v} + B8\frac{1}{v^2} \quad (20)$$

With the bracket expressed as below:

$$B1 = \left(\frac{c_{f1}}{c_{f2}}\frac{C_{D0}\rho S}{2}\right); B2 = \left(\frac{c_{f1}C_{D0}\rho S}{2}\right); B3 = \left(\frac{c_{f1}}{c_{f2}}m\right); B4 = (C_{f1}m); B5 = \frac{c_{f1}}{c_{f2}}mg\sin\gamma; B6 = C_{f1}mg\sin\gamma; B7 = \left(\frac{c_{f1}}{c_{f2}}\frac{2C_{D2}m^2g^2}{\rho S}\right); B8 = \left(c_{f1}\frac{2C_{D2}m^2g^2}{\rho S}\right)$$

The above coefficients depend on air density and vary with altitude. The fuel consumption is the integral of fuel rate with respect to time (Equation 21):

$$FC = \int_0^{T_f}[B1v^3 + (B2 + B3\frac{dv}{ds})v^2 + (B4\frac{dv}{ds} + B5) + B6 + B7\frac{1}{v} + B8\frac{1}{v^2}]dt \quad (21)$$

with T_f the final time.

The fuel consumption is influenced by different factors. Many research projects investigated the impact of altitude, speed and path angle [17-20]. For some aircraft such as regional and business jets (not large jet), flying at a fixed flight path angle and constant Mach/calibrated-airspeed results in lower fuel consumption compared to standard descents at idle-thrust and constant Mach/calibrated airspeed [21]. Other researchers implemented CDA under traffic conditions based on air traffic simulation and BADA fuel model. They founded that the enabling large or heavy aircraft to engage in CDA achieved higher fuel benefits [22].

Considering $dt = ds/v$ the integral (21) can be written with respect to v and s (Equations 22 and 23):

$$FC = \int_0^{s}\left[B1v^2 + (B2 + B3\frac{dv}{ds})v + \left(B4\frac{dv}{ds} + B5\right) + B6\frac{1}{v} + B7\frac{1}{v^2} + B8\frac{1}{v^3}\right]ds \quad (22)$$

$$FC = \int_0^{s}\left[B1v^2 + B2v + B5 + B6\frac{1}{v} + B7\frac{1}{v^2} + B8\frac{1}{v^2}\right]ds + \int_{v_0}^{v_f}\left[B3v + B4\right]dv \quad (23)$$

with v_0 and v_f respectively the initial and the final speed.

In order to simplify this complicated integral of the fuel rate, some assumptions are stated. First, if the speed is constant the second term of integral can be removed. The trajectories have been previously discretized in interval segment. This module uses the same three-dimension interval segments to calculate the fuel burn. The integral can be considered as a discretized sum of fuel consumption on each interval segment of the trajectory along the whole distance from top of descent to touchdown.

This formula is implemented in the module for fuel consumption taking into account all the mentioned assumptions and considerations.

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The module associated to fuel assessment aims to provide the value of fuel consumption along each path segmentation interval, and along the whole generated trajectories. The system can realize this service only if it receive data from BADA aircraft parameters database and structured trajectories in input as shown in figure below (Fig. 9).

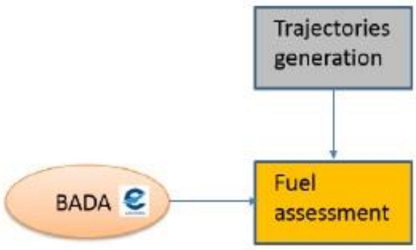

Fig. 9. Fuel assessment module.

Furthermore, it delivers the percentage of fuel saving for the whole generated CDA trajectories with respect to the reference trajectory.

Optimized Trajectories Selection

The last module performs the algorithms for selecting of the optimal trajectory taking into account the generated trajectories (recalculated after the verification of potential collisions) and fuel consumption data resulted from fuel assessment sub-system.

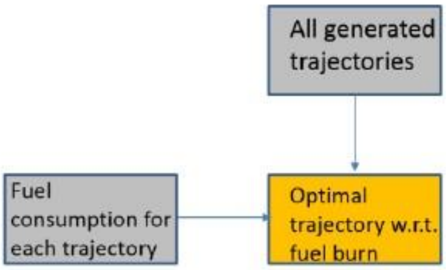

Fig. 10. Optimal trajectory module.

The optimal trajectory selection tool compares the percentage of fuel saving of all trajectories, and returns those that has consumed the minimum fuel, resulting in the best solution for fuel saving and the consequently environmental impact (Fig. 10).

The following sections present how the system of CCDA works to provide the final optimal trajectory based on appropriate considerations and discussions of results.

IV. APPLICATIONS

The simulations are reported in following sub-sections. The scenario focuses on the ATM operating environment of the Naples Airport (LIRN ICAO code identification), in the Campania Region (Figs. 11 and 12).

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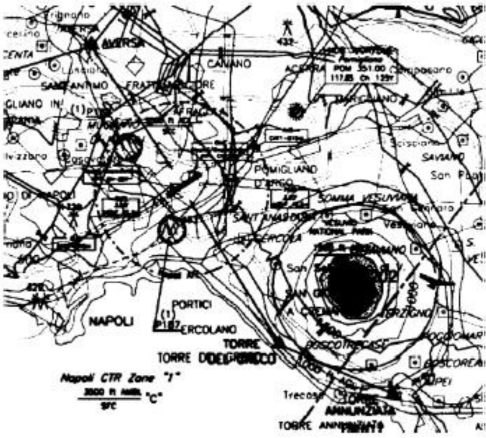

Fig. 11. Naples aerodrome traffic zone [23].


Fig. 12. The territorial framework of the study case.

This zone is particularly affected by aircraft noise due to the proximity of the runway/airport to the highly populated city of Naples. The following figure shows a zoom of the airport, in which it is possible to have an idea about the vicinity of the anthropic buildings (Fig. 13).


Fig. 13. Zoomed framework of the study case.

These issues result in noise abatement procedures and approach procedure restrictions. More limitations to the trajectory implementation in the approach phase are also the terrain profile rich of the mountains.

The conventional trajectory compliance to the noise abatement procedures is defined by a fixed-flight-path angle and constant-speed and satisfy the arrival procedures according to the Instrumental Approach Chart ILS Z RWY 06 [23].

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V. RESULTS AND DISCUSSION

The path angle characterizes the fuel flow rate because the existing of its value is the main difference between the level-flight path and continuous-descent path. Increasing the path angle, the fuel consumption decreases. Usually the range of path angle is [-2, -4] degrees. The terminal maneuver area of the Naples airport is used as ATM reference scenario. The simulations demonstrate the possibility of achieving two different CDAs technics: CDAs with a constant path angle up to 4 degree, and CDAs with an optimized descent profile at different altitude and constant path angle. In the first case, the top of descent (TOD) is calculated according to predefined angle. In the second case, the trajectory follows a path at a fixed altitude up to intercept the glide path for the descent at constant path angle. The following figures show separately the elaborations for a set of CDAs at different path angles (respectively 3.5° in blue, 3.7° in green, and 4° in red) and a set of CDAs compared to the step-down trajectory with fixed angle to 3°.5.

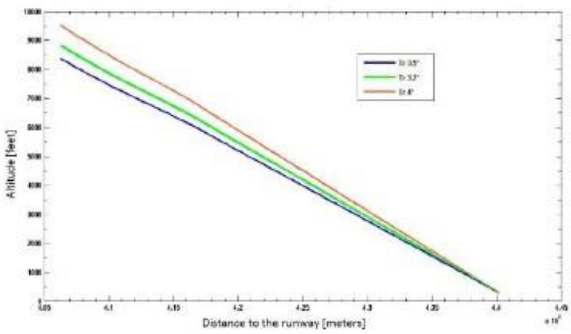

Fig 14. Comparison between CDAs at different path angle.

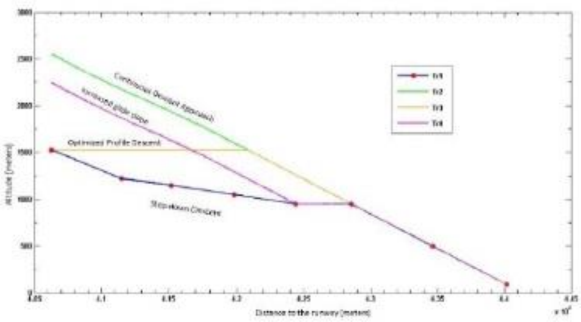

Fig. 15. Comparison between step-down trajectory and different CDAs technics.

As shown in the figures all CDAs report TODs higher than the conventional step-down descent.

In practices, many CDA procedures are implemented in order to intercept the Glide Path of ILS systems (typically of 3.5 degrees). The component for intercepting the path angle has generally within a range of 10 MN. This could limit the implementation of CDA with great path angle. The following figure shows the conventional trajectory at 3°.5 (green) compared with a CDA at 4° (blue) and a CDA generated starting from a glide path at 3°.5, then a level flight segment of 2NM, and finally a final straight segment at 4° (red).

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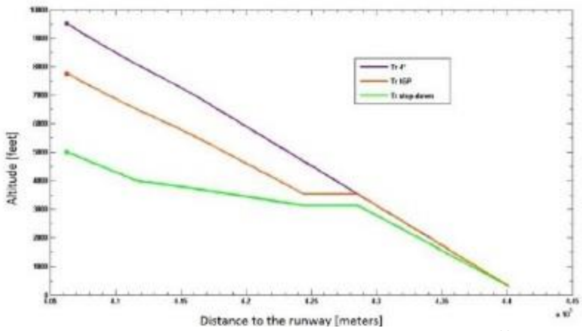

Fig. 16. Comparison between step-down trajectory and CDAs at different path angle.

A procedure based on increasing the slope of the final approach procedure and a level flight segment of at least 2 MN before final approach fix (FAF) could be preferred to today's procedures because its implementation reduces noise and emissions in the final approach phase maintaining the compliance with current limitations and rules of air.

The efficiency in terms of fuel consumption can be analysed starting from the calculation of fuel burn saving for a single flight in TMA environment. Even if the capability of aircraft to perform CDAs is out of the scope, an example is provided here, adopting A300B4-622 parameters provided into BADA User Manual [16]. Referring to the figures previously reported (Figs. 14-16), the generated trajectories at different path angle and different altitude are analysed with respect to the fuel consumption. The implementation of fuel consumption formula demonstrates a reduction in percentage with respect to conventional trajectories. Furthermore, they report a better fuel burn saving for a greater path angle. Aircraft performance dataset is here used in order to provide an example of fuel consumption starting from TEM BADA equation. This methodology of implementing CDA and calculating fuel burn consumption is independent from used information. The efficiency in terms of saving of fuel burn in TMA is analysed comparing conventional trajectory with different CDAs. The fuel consumption formula is implemented considering the geopotential pressure altitude equal to geodetic altitude, and the true airspeed equal to ground speed (that is ISA and no wind condition) and constant.

The analysis on three main study cases in which is summarized in the following tables including the following data:

- The considered trajectory and glide path angle;
- The distance flown in 3D space expressed in nautical miles [NM];
- The fuel burn in kilogram [kg] for the approach and landing phases;
- The fuel saving with respect to the reference trajectory expressed in percentage [%].

The following Table 1 shows the analysis for CDAs at different glide path angles shown in the Fig. 12.

Table 1. CDAs at different glide path angles.

Trajectory and glide path angle	Distance to runway [NM]	Fuel burn [kg]	Fuel saving percentage [%]
CDA, 3°.5	21.77	145.07	0
CDA, 3°.7	21.77	127.52	12.1
CDA, 4°	21.78	101.25	30.21

The second case is referred to Fig. 13, and the comparison between step-down trajectory and different CDAs technics is reported in the table below (Table 2):

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Table 2. CDAs vs Stepdown trajectory.

Trajectory and glide path angle	Distance to runway [NM]	Fuel burn [kg]	Fuel saving percentage [%]
Stepdown, 3°.5	21.73	272.3	0
CDA, 3°.5	21.77	145.07	46.72
OPD, 3°.5	21.75	271	0.48
IGS, 3°.5 – 4°	21.72	183.5	32.61

With respect to step-down approach, the theoretical CDAs with constant angle fixed to 3.5 degrees as for conventional trajectory, lead up to 47% of fuel saving. The optimized profile descent and increased glide path provide respectively a value of 0.5% and 33% w.r.t. CDA at 3.5 degrees. Among CDAs with different constant path angle the path with 4 degrees have a fuel saving up to 62%. Considering the Fig. 14, an increased glide path starting from 3.5 degree up to 4 degrees led to a percentage of fuel saving of 38%. In the analysis the mass of aircraft is considered as a constant, the vertical path is assumed as a perfect vertical profile not considering the variability of speed and aircraft mass. Therefore, the fuel consumption is overestimated. Another consideration about the efficiency is that CDAs should evaluate their integration with not CDAs in low and high density of air traffic. This consideration results in errors in vertical and speed profile generation.

VI. CONCLUSION

This paper provided a study of Curved and Continuous Descent Approach for Efficient Air Transport System, reported the defection of suitable mathematical model for fuel consumption evaluation during descent and indicated and discussed high-level requirements for the implementation of an automatic Continuous Descent Approach trajectory generation system. A list of performance indicators useful to assess benefits of CDAs has been also reported in the paper and possible future improvements and integrations of the proposed system have been provided. In particular, considerations on the efficiency of a generic flight in TMA have been emphasized and studied in terms of fuel burn, indicating that significant fuel savings can be achieved using CDA techniques with respect to conventional descent profile. Therefore, the Curved and Continuous Descent Approach profiles are preferable to the step-down trajectories currently in use, reducing the environmental impact in terms of fuel consumption. These trajectories with flight path angle at different altitude of TOD can provide support to the operational feasibility of CDA procedures for air traffic flow in TMA. The comparison of different flight profiles allows identifying the optimal profile with respect to fuel consumption.

VII. ACKNOWLEDGMENTS

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REFERENCES

[1] ICAO, "Continuous Descent Operations (CDO) Manual – Doc 9931/AN/476," Montreal, 1st edition, 2010.
[2] EUROCONTROL Continuous Descend Approach – Implementation Guidance Information, 2008.
[3] ICAO, "Rules of Air", International Civil Aviation Organisation, 2005.
[4] ICAO, "Doc 9613 - Performance-based Navigation Manual", International Civil Aviation Organisation, 3rd edition, 2012.
[5] JP.Clarke, NT. Ho, L. Ren, JA. Brown, KR. Elmer, K. Zou, C. Hunting, DL. Mcgregor, BN. Shivashankare, KO. Tong, AW. Warren, JK. Wat, "Continuous Descent Approach: Design and Flight Test for Louisville International Airport," Journal of Aircraft, vol.41, no.5 , pp.1054–1066, 2004.

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ISSN (Print): 2347-6710

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 6, Issue 6, June 2017

[6] J-P. Clarke, J. Brooks, G. Nagle, A. Scacchioli, W. White, SR.Liu, "Optimized Profile Descent Arrivals at Los Angeles International Airport," Journal of Aircraft, 2015.
[7] OPTIMAL Final publishable report, 2008.
[8] H. de Jonge, S. Törner, ERAT ARN D4-1 "Concept of Operations Arlanda Airport," NLR/LFV, 2009.
[9] SOURDINE, Final Report, 2001.
[10] den Boer R et al. "Sourdine II Final Report", NLR, 2006.
[11] EUROCONTROL Experimental Centre (EEC), "Point Merge Integration of Arrival Flows Enabling Extensive RNAV Application and Continuous Descent," version 2.0, 2010.
[12] B. Favennec, E. Hoffman, A. Trzmiel, F. Vergne, K. Zeghal, "The Point Merge Arrival Flow Integration Technique: Towards More Complex Environments and Advanced Continuous Descent", 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO). South Carolina, 2009.
[13] A. Errico, V. Di Vito, L. Federico, "Study on Continuous Descent Operation for Efficient Air Transport System," 16th AIAA Aviation Technology, Integration, and Operations Conference (ATIO). Washington, D.C., 2016.
[14] TA. Driscoll, B. Fornberg, "Interpolation in the limit of increasingly flat radial basis functions", Computers & Mathematics with Applications, vol. 43, no. 3–5, pp. 413–422, 2002.
[15] D. Delahaye, S. Puechmorel, P. Tsiotras, E. Feron, "Mathematical Models for Aircraft Trajectory Design : A Survey", Lecture notes in Electrical Engineering, vol.3, no. 12, pp 205-247,2014.
[16] BADA User Manual, EUROCONTROL, 2004.
[17] L. Jin, Y. Cao, D. Sun, "Investigation of Potential Fuel Saving due to Continuous Descent Approach," Journal of Aircraft, 2013.
[18] T.Thompson, B. Miller, C. Murphy, S.Augustine, T. White ,S. Souihi, "Environmental Impacts of Continuous-descent Operations in Paris and New York Regions," Tenth USA/Europe Air Traffic Management Research and Development Seminar, 2013.
[19] Y. Cao,T. Kotegawa, J. Post, D. Sun,D. DeLaurentis, "Evaluation of Continuous Descent Approach as a Standard Terminal Airspace Operation," Ninth USA/Europe Air Traffic Management Research and Development Seminar, 2011.
[20] E. Itoh, NK. Wickramasinghe, H. Hirabayashi, K. Uejima, S. Fukushima, "Analyzing Feasibility of Continuous Descent Operation Following Fixed-flight Path Angle from Oceanic Route to Tokyo International Airport," AIAA Modeling and Simulation Technologies Conference, AIAA SciTech Forum, 2016.
[21] T. Nikoleris, GB. Chatterji, RA. Coppenbarger, "Comparison of Fuel Consumption of Descent Trajectories Under Arrival Metering," Journal of Aircraft, Vol. 53, No. 6, pp. 1853-1864,2016.
[22] Y. Cao, L. Jin, V.Nguyen, P. Nguyen, S. Landry, D. Sun, P. Joseph, "Evaluation of Fuel Benefits Depending on Continuous Descent Approach Procedures," Air Traffic Control Quarterly, Vol. 22, No. 3, pp. 251-275, 2014.
[23] http://www.enav.it, AIP