COLLISION RISK STUDIES WITH 6DOF FLIGHT SIMULATIONS WHEN AERODROME OBSTACLE STANDARDS CANNOT BE MET

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Abstract

This paper presents an effective methodology to assess the safety of aircraft operations when aerodrome obstacle standards cannot be met. The research addresses the cases of potential airplane impact with on-ground obstacles after an engine failure. The discussion focuses on how statistical studies can be supported by deterministic analyses of flight trajectories generated with 6 degree-of-freedom (6DoF) flight simulations. The proposed approach is illustrated by introducing a practical example coming from the authors' professional experience; in the selected scenario a hypothetical wind farm has to be located in proximity of an aerodrome but some of the wind turbines intrude the conventional airspace required by ICAO to ensure safe and regular aircraft operations. The paper presents the relevant safety requirements applicable around airports and introduces a preliminary evaluation technique of the theoretical collision risk (CR) based on the open source flight dynamics model (FDM) software JSBSim. Finally, a Monte Carlo analysis is presented as an additional step to refine the CR assessment.

1 Introduction

The safety of aircraft operations in presence of aerodrome obstacle is ensured by strict requirements on the obstacle relative positioning with respect to conventional volumes or airspaces. Erecting tall wind turbines (90 meter or more above ground level) near airports presents special challenges to wind energy programs when it comes to the choice of a specific site, and is considered a growing problem by airport authorities. At the same time, grounds around airports are often targeted by companies developing wind turbine parks as a preferable option for their plans. Usually these areas are relatively unpopulated, due to noise hindrance constraints, and most of the times do not present large obstacles that could cause wind blockage for the wind turbines. However, the construction of wind farms may intrude the airspace that is required to ensure safe and regular aircraft operations at the airport.

The present paper, which evolves from the work of De Marco *et al.* [1], goes into some details concerning the safety requirements that apply around airports and how a theoretical collision risk (CR) can be evaluated using Monte Carlo flight simulations.

It is well known in aeronautics that rules are defined by authorities on the basis of some historical evidence. Usually a specific airworthiness problem such as the airborne collision with an on-ground obstacle is correlated to a number of accidents occurred in the past. The historical series were used by the authorities to define the clearance rules and a set of virtual volumes surrounding airfields. When an obstacle is designed and positioned in such a way that it intrudes, even slightly, one of the prescribed volumes, the builder is required to provide an "aeronautical study". The study has to demonstrate that the obstacle does not modify the established safety level and the regularity of flight operations [2, 3].

Aeronautical studies nowadays may take advantage of the availability of advanced engineering flight simulation software to select a range of critical flight situations as a base for subsequent statistical studies for collision risk assessment. The flight simulation results presented in this paper were obtained with JSBSim [4, 5, 6], an open source 6-DoF (Degree-of-Freedom) flight dynamics model (FDM) software library (`www.jsbsim.org`). JSBSim has been used in the last decade to support flight test research activities of the Aircraft Design and AeroflightDynamics Group (ADAG, `www.adag.unina.it`) at the University of Naples Federico II [7, 8]. Other examples exist of JSBSim applications in Air Traffic Management studies, e.g. see Barragán Montes *et al.* [9]. In the present paper the autopilot features of the library are used to simulate human behaviour in post-failure situations and the scripting capabilities are used to automate simulations.

2 Wind farms and regulatory issues

Wind turbines located near airports are associated in general to four main issues that may affect the safety of aircraft operations:

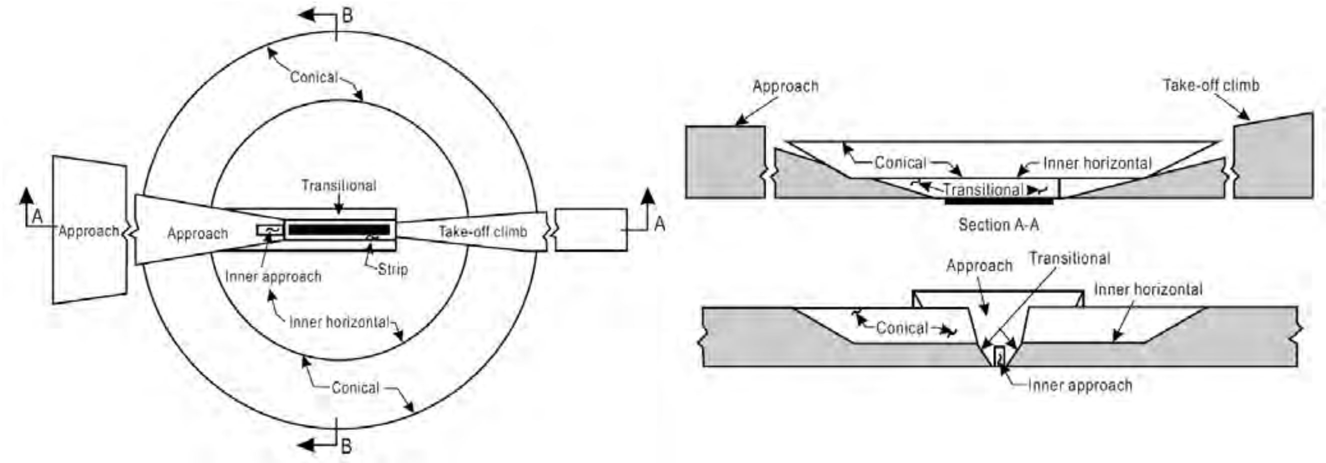
- Collision risk [2, 3, 10, 13].
- Aircraft operational impact (interference with navigation procedures) [10, 13].
- Disturbances of radar, navigation aids and communication aids [11].
- Wind Hindrance (strong turbine wake interference with local wind, no specific international regulations exist on this topic).

Only the last of the above safety issues is specific to wind farms, the first three being generally associated to all types of on-ground obstacles.

This paper deals primary with the CR assessment with a specific focus on wind farms. The applicable regulatory framework for the CR safety aspects is shortly summarized below.

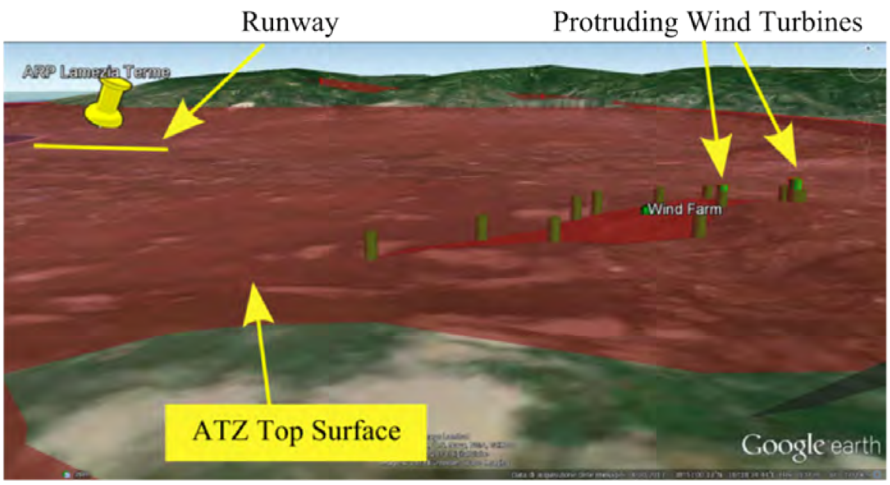
The CR is mainly dealt with by International Civil Aviation Organization Annex 14 and other related documents [2, 10, 13], and sometimes by some local regulations (e. g. [3] for Italy). The objectives of these specifications are to define the airspace (volumes and their boundary surfaces) around aerodromes to be maintained free from obstacles so as to permit the intended aeroplane operations at the aerodromes to be conducted safely and to prevent the aerodromes from becoming unusable by the growth of obstacles around the aerodromes. This is achieved by establishing a series of obstacle limitation surfaces that define the limits to which objects may project into the airspace. The safety issue comes when an obstacle, such as a wind turbine, protrudes one of the defined Obstacle Limitation Surfaces (OLS). The OLS define the maximum height that obstacles near airports are allowed to have, see Fig. 1a. Usually the boundary named Inner Horizontal Surface (IHS) or Conical Surface (CS) is of major interest, when it comes to erecting wind turbines. The IHS is a cylindrical surface of 45 m height, with a radius ranging from 2 to 4 km, depending on the runway type. The CS slopes outward from the IHS (see Fig. 1a) with a slope of 5% up to a height of 80 to 145 m, also depending on the runway reference length. The Aerodrome Traffic Zone (ATZ) is the airspace of defined dimensions established around an aerodrome for the control and protection of airport operations. A standard ATZ has a cylindrical shape with a height above ground level of 600 m (2000 ft) and a radius of 9 km (5 nmi) centered on the Airport Reference Point (ARP). The Outer Horizontal Surface (OHS) is a cylindrical surface of 150 m height with a radius of 15 km (9 nmi) centered on the ARP. In case an obstacle protrudes one of the above surfaces, an aeronautical study is required to demonstrate that the obstacle does not affect the safety and regularity of the operations to/from the airport. However there are no guidelines in the regulations on how this task has to be carried out.

In the next section a practical scenario will be presented where a potential protrusion issue arises. The example refers to the siting of a wind farm in the proximity of an aerodrome. It must be observed that in the case of aircraft or rotorcraft collision with wind turbines, the United States National Transportation Safety Board (`www.ntsb.gov`) reports only one airborne accident of this type occurred since 1990



(a)Top and side views of some of the most important ICAO Obstacle Limitation Surfaces.

(b)The LICA airport runway (flag), the wind farm area (red polygon), the ATZ border (red line), and the two reporting points (blue arrow heads).



(c)Wind farm with some turbines that exceed the ATZ top surface.

Fig. 1 Limitation surfaces and selected scenario.

to present, over a total of 140 000 accidents in North America. It is also true that only in the last two decades we have seen a significant growth of wind farms all over the world. This will enforce the international authorities to release in the near future a specific regulation for siting new wind turbines near aerodromes.

3 Example scenario and selection of hazardous trajectories

A hypothetical wind farm to be located in the proximity of Lamezia Terme International Airport (LICA), see Fig. 1b, is the practical case considered in this work. LICA is the principal airport of Calabria, the southernmost region of the Italian peninsula, with its 2 millions of passengers per year (`www.assaeroporti.it`). This aerodrome has only one asphalt runway of 2.4 km in the directions 10/28 and an elevation of 12 m (above mean sea level, AMSL). The construction of a large wind farm of 21 turbines is planned in the nearby area named Piano Barone. Wind turbines have a total height of 151 m above ground and rotor diameter between 80 and 92 m. The desired location of the plant is on the south-east border of the ATZ of the airport. The situation is visualized by the Google Earth view of Fig. 1b. The planned turbines are located around 9 km from the airport, at 8.6 km from the PONTILE SIR (S1) and at 9.6 km from GIRIFALCO (SE1) reporting points. These points are two of a number of VFR air navigation references. The closest ones to the runway, such as S1 and SE1, are used by airplanes to approach the landing circuit.

In the given example some of the turbines intrude one of the OLS as shown by Fig. 1c. This is a case when an aeronautical study is required to finalize the authorization procedures to build the plant. The provider of this study has to deal with all the possible air routes that airplanes can fly according to the local regulations and highlight the most critical ones. For each of these critical scenarios a CR assessment has to be performed. The selection of potentially dangerous trajectories must necessarily be supported by airport charts (also known as 'standard aerodrome & procedure charts'). In these documents, usually compiled by the local airworthiness authority (in our case the Italian ENAV), all the feasible routes are shown. The routes are divided into flight segments (take-off, landing, circling, etc.) and operating modes (Instrumental/Visual Flight Rule, IFR/VFR). An extract of this document for LICA airport is shown in Fig. 2.

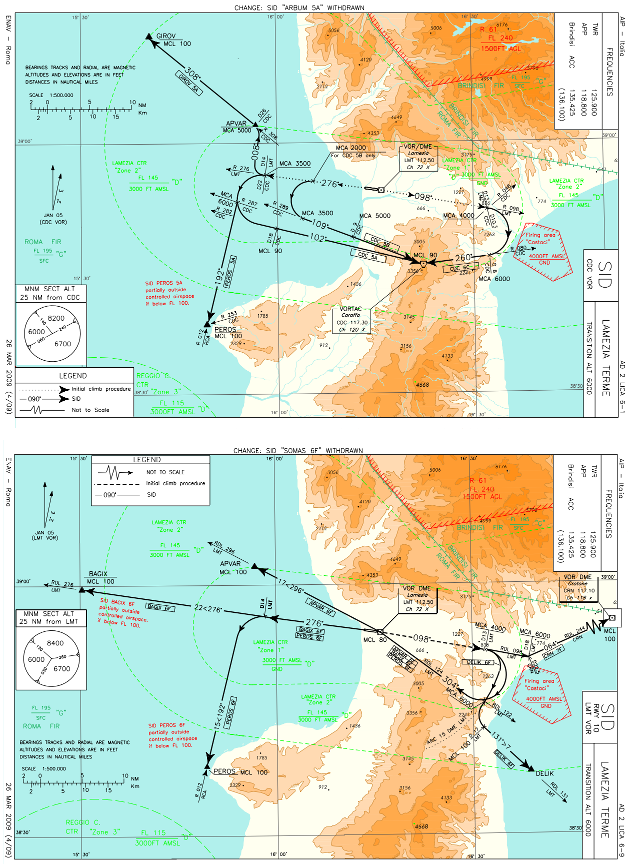


Fig. 2 Example of a Standard Instrumental Departure (SID) charts for LICA airport.

From the analysis of the charts it comes out that the most critical trajectory is a nominal VFR route crossing the Control Traffic Zone (CTR, or Controlled Traffic Region) of Lamezia Terme, and passing over the expected wind farm area (see Fig. 1b for details). The ATZ is included into the CTR, which is a radar controlled area by LICA tower. The selected route is critical when:

- The pilot flies under the prescribed vertical distance of 305 m (1000 ft) from the highest obstacle in a radius of 600 m (even if not indicated on the maps). When this distance is added to the obstacle height a clearance altitude is defined and named Lowest Safe Alti-

tude (LSALT). Typically, for each new obstacle accepted by authorities the LSALT is updated accordingly.
- An engine failure occurs, forcing the pilot to perform an evasive manoeuvre and an emergency landing.
- A gust brings the airplane under the LSALT.

Obviously, a critical event occurs when one or more of the above situations take place at the same time.

Starting from the above scenario, having established a reference flight situation, a deterministic study can be carried out to explore the space of critical events. If a suitable subset of fatal events is determined, this can be used to support the estimation of CR.

In the simplest case one representative airplane model can be chosen, namely a single propeller general aviation aircraft. This choice seems acceptable considering that larger airplanes, especially jet transport airplanes, fly at higher flight altitudes and are more strictly controlled by Air Traffic Control (ATC) service. The next section introduces the framework chosen for engineering flight simulations of critical trajectories.

4 Engineering flight simulations with JSBSim

JSBSim is a high-fidelity, 6-DoF (Degree-of-Freedom), general purpose, flight dynamics model (FDM) software library written in the C++ programming languages [4, 5].

The JSBSim library routines propagate the simulated state of an aircraft given inputs provided via a script or issued from a larger simulation application. The inputs can be processed through arbitrary flight control laws, with the outputs generated being used to control the aircraft. Aircraft control and other systems, engines, etc. are all defined in various files in a codified XML (eXtensible Markup Language) format. JSBSim can be run as a standalone, batch-mode flight simulator (no graphical displays), or integrated with other software applications. The FDM is essentially the physics/math model that defines the movement of the aircraft, under the

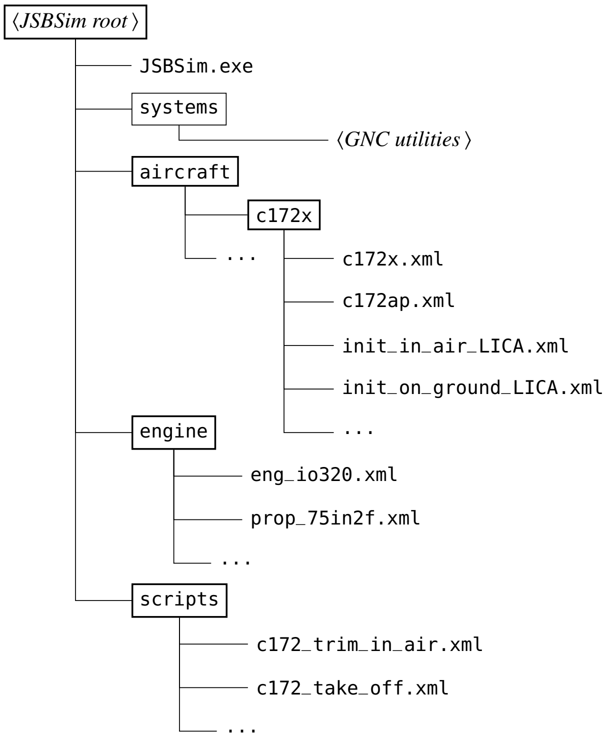


Fig. 3 Organization of JSBSim files.

forces and moments applied to it using the various control mechanisms and from the forces of different nature.

When JSBSim is used as a standalone program, typically, it takes input from a script file and various vehicle configuration files. The library can also be incorporated into a larger flight simulator implementation that includes a visual system. The most notable examples of the use of JSBSim are currently seen in a number of flight simulation applications like: FlightGear (`www.flightgear.org`), Outerra (`www.outterra.com`), Paparazzi (`paparazzi.enac.fr`), and OpenEaagles (`www.openeaagle.org`). JSBSim is also used to drive the motion-based research simulators at the University of Naples, Italy [12], and in the Institute of Flight System Dynamics and Institute of Aeronautics and Astronautics at RWTH Aachen University in Germany (`www.ilr.rwth-aachen.de`).

The scripting feature of JSBSim is suitable for the automatic preparation of flight simulations. In particular, the user has the possibility to set initial flight conditions — e. g. airplane in trimmed flight along the critical route, at a given altitude, with a given heading. At specified conditions along the initial trajectory a number of critical events can be triggered, all in a specific XML-based meta-language named JSBSim-ML.

The library also provides fine-tuned automatic control logic and laws for the many available aircraft models. These have been used to model pilot behaviour, like the ability to follow a certain nominal route or the reaction time to select a new trajectory in a simulation with failures.

The basic JSBSim simulation needs only three XML files:

- The FDM configuration file of the chosen aircraft. This file contains the definition of all the aerodynamics, inertial and systems characteristics.
- An initialization file where all the properties of the aircraft are set to a certain value before the propagation of the state (i.e. initial conditions).
- A simulation script file with a sequence of optional control "events" of various types. The events are used in this case to trigger some "pre-cooked" modifications of command positions.

In addition to the script, the 6-DoF flight is subject to the automatic control laws implemented in the dedicated section of the FDM configuration file.

4.1 Flight dynamics model of a Cessna 172

The above discussed scenario makes sense for single-engine airplanes. Similar scenarios, namely the failure of one engine, applied to multiple-engine vehicles are obviously not as critical as the case of a single-engine airborne vehicle that remains completely unpowered. The failure of all engines of a multiple-engine aircraft is possible but is much less probable.

In this study a representative airplane model of single propeller general aviation aircraft has been chosen: a Cessna 172 Skyhawk, a four-seat, single-engine, high-wing aircraft manufactured by Cessna Aircraft Company. The FDM configuration file and a complete set of companion files for the Cessna 172 are provided with the official distribution of JSBSim. The organization of the main input files and folders, adapted to the proposed simulation scenario, is shown in Fig. 3. The main configuration file (`c172x.xml`) contains several sections, each identified by a XML marker or tag. These sections define all the components of the aircraft mathematical model, such as: geometry, mass distribution, landing gears, propulsive system, flight control system, aerodynamics. The aerodynamic model is a full-blown aerodynamic database of the aircraft.

A detailed description of the airplane's FDM configuration files, of the initialization and script files (e. g. `aircraft/c172x/init_*.xml`, `scripts/c172x_*.xml`, etc.) used for the simulations as well as a summary of characteristics and performance data of the Cessna 172 Skyhawk are given in [1].

4.2 Setup of the simulations

A preliminary analysis of the airport charts (see Fig. 2) revealed a potential ATZ-crossing hazardous trajectory, thus the aircraft starting point in the simulation experiments is placed at a given point on the OHS border, located at North-West of LICA airport (Fig. 4 and Fig. 5). Therefore, the initial flight situation selected for the present study is a VFR route crossing the ATZ of Lamezia Terme and coursed at cruise speed. The typical starting situation for each simulated flight is the following: (a) the aircraft is placed on a route headed to GIRIFALCO (SE1) reference point (121 deg); (b) the altitude is set to 720 m (2360 ft); (c) speed is set to 58 m/s (113 kn). The initial altitude is the lowest possible allowed by the authorities, namely the LSALT, a height of 1000 ft above the highest turbine of the hypothetical wind farm. The initial speed is approximately the cruise speed.

4.3 Preliminary estimation of collision probability

Several preliminary simulations have been performed in order to establish a plausible locus of points along the nominal route associated to engine failures and subsequent collisions. Considering the nominal route shown in Fig. 4, the event that triggers the engine failure is the distance to the wind farm area. After the failure, to avoid a

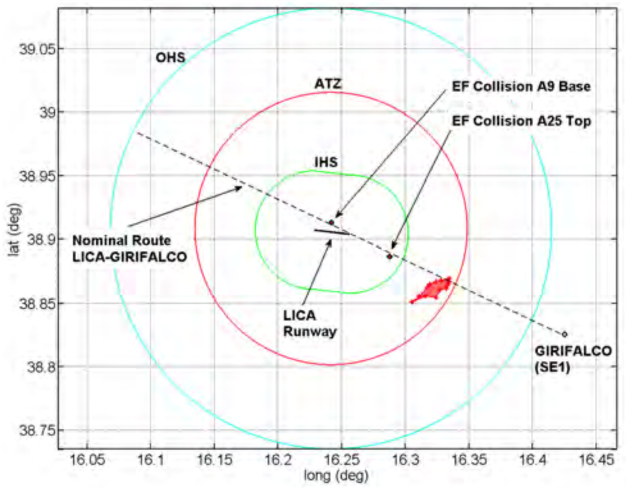


Fig. 4 Nominal VFR from LICA to GIRIFALCO (SE1) route and locations of critical events

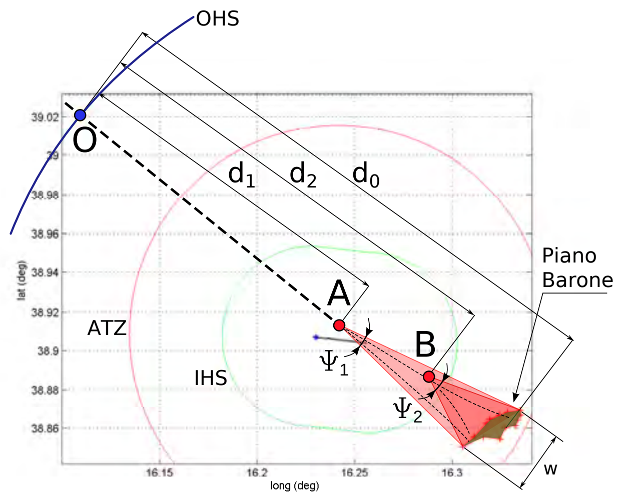


Fig. 5 Major geometrical data for the collision risk assessment of a flypast course over a hypothetical wind farm.

collision with the farm, the pilot must perform a turn, left or right, to point to a new safety course. The reaction time of the pilot is set to 7.5 s to simulate a sort of first disorientation in case of bad weather condition (human factor) or just the pursue of a safety landing spot before the turn manoeuvre.

As discussed by De Marco *et al.* [1], a critical zone along the selected route (interval of distances from the farm) can be defined. When the engine failure occurs too close to the wind farm area the pilot has poor chances to avoid entering the volume occupied by the plant. When the airplane reaches a given point along the route every failure will not end up with a critical trajectory. The basic schema of this scenario is depicted in Fig. 5. The critical interval is given by segment AB. If an engine failure occurs before reaching point A the airplane ends its gliding trajectory always outside of the wind farm area, even with no heading change. This situation is similar for all the trajectories with failure after point B, where the aircraft can safety overtake the wind farm. When the engine failure occurs between point A and B of the nominal route, the aircraft trajectory terminates in the plant volume only if corrected courses remain confined in the volume given by angles Ψ_1 and Ψ_2. The two critical points A and B are determined by inspecting the simulated trajectories. Point A leads to a collision with the base of the lowest tower (A9). Point B leads to a collision with the top of the highest rotor (A25). The post-failure trajectory analysis defines an enveloping rectangle Σ (see Fig. 6). This rectangle encloses the projection of the wind farm in a vertical plane, from the leftmost tower to the rightmost and from the base (A9 base) of the lowest tower to the top of the highest rotor (A25 top).

A simple theoretical CR assessment for the basic scenario introduced above can be performed on the basis of trajectory data obtained with deterministic simulations. To support the assumptions on the problem geometry and on pilot's behaviour, a probability of engine failure also need to be accounted for.

Considering Fig. 5, The probability P_1 that a post-failure trajectory enters the critical rectangle of Fig. 6 is given by:

$$P_1 = \frac{d_2 - d_1}{d_0} \qquad (1)$$

By evaluating distances d_0, d_1 and d_2 (see [1] for details) this probability has a numerical value $P_1 = 0.19$. The number P_1 is a 'vertical' collision index not accounting for heading deviations. Similarly, a 'horizontal' collision index P_2 is determined by the formula:

$$P_2 = \frac{1}{2}\frac{\Psi_2 - \Psi_1}{2\pi} \qquad (2)$$

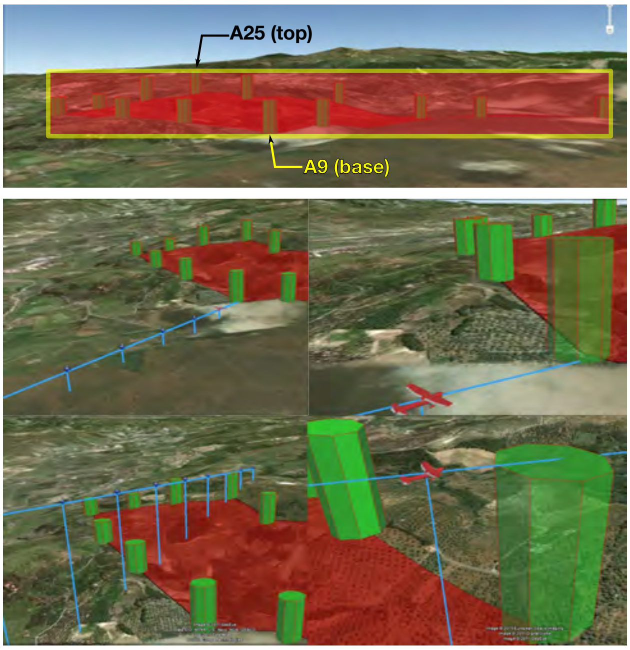


Fig. 6 (Top) Collision rectangle. (Bottom) Corner cases of simulated trajectories colliding with towers of the farm (see Fig. 4, EF Collisions).

By evaluating angles Ψ_1 and Ψ_2 depicted in Fig. 5 the horizontal probability index has been found to have a value $P_2 = 0.089$.

Moreover, the probability P_3 that a trajectory entering the critical rectangle Σ actually collides with one of the wind turbines depends on their horizontal spacing. This index is evaluated by the formula:

$$P_3 = \frac{nD}{w} \tag{3}$$

where n is the number of wind turbines, D is the charachteristic rotor diameter, and w is the width of the region Σ. The actual values considered in this study are $n = 21$, $D = 86\,\text{m}$, $w = 3274\,\text{m}$, yielding a probability $P_3 = 0.55$.

The estimation of the theoretical CR is obtained by combining the three indices defined above with the engine failure risk, P_{EF}, normally of the order of 10^{-5}. Therefore, according to the above scenario and assumptions, the theoretical probability P_{theor} that a general aviation aircraft with similar characteristics similar to the selected one impacts a wind turbine of the plant after an engine failure is estimated as:

$$\begin{aligned} P_{\text{theor}} &= P_1 \cdot P_2 \cdot P_3 \cdot P_{\text{EF}} \\ &= 0.19 \cdot 0.089 \cdot 0.55 \cdot 10^{-5} \\ &= 0.0093 \cdot 10^{-5} = 9.3 \cdot 10^{-8} \end{aligned} \tag{4}$$

The above value of CR is compliant with the acceptability threshold of 10^{-7} required by the international regulations on Collision Risk Model (CRM) [14]. The threshold of 10^{-7} is actually used for probabilistic studies on collisions with on-ground obstacles at take-off/landing or after a missed precision approach. Since the authorities do not give a specific recommendation on the CR acceptability threshold for above-obstacle flyover routes, the value 10^{-7} is chosen here as a preliminary reference for further and finer investigations.

5 Monte Carlo simulations

The theoretical P_{theor} obtained with a simplified CR evaluation approach can be refined with a Monte Carlo study. The random variables taken into account in the analysis are: the initial altitude h_0 of the route, the time t_{fail} of the engine failure along the route, and the final chased heading ψ_{safe} for a 'safe' emergency landing.

No real data are available for the problem under study therefore Monte Carlo simulations have to be based on assumed probability distribution functions (pdf) of the selected random variables. In this particular case, the initial altitude h_0 is dispersed with a normal distribution (see Fig. 7), having a mean value equal to the nominal safe altitude LSALT, and standard deviation of almost 100 ft. These particular values are chosen considering the typical conduct of flight in ATZ crowded areas. The time of engine failure can be assumed equiprobable during all the simulated flights, therefore an uniform pdf of t_{fail} is selected. Similarly, a uniform pdf is chosen for the final heading ψ_{safe}. The limits of the final course of the airplane are set to $\pm 90\,\text{deg}$ from the initial heading assuming that an engine failure occurrence forces the pilot to search a safe emergency landing spot in his field of view (about 180 deg).

By varying the three quantities $(h_0, t_{\text{fail}}, \psi_{\text{safe}})$ in their own sets of generated random values a

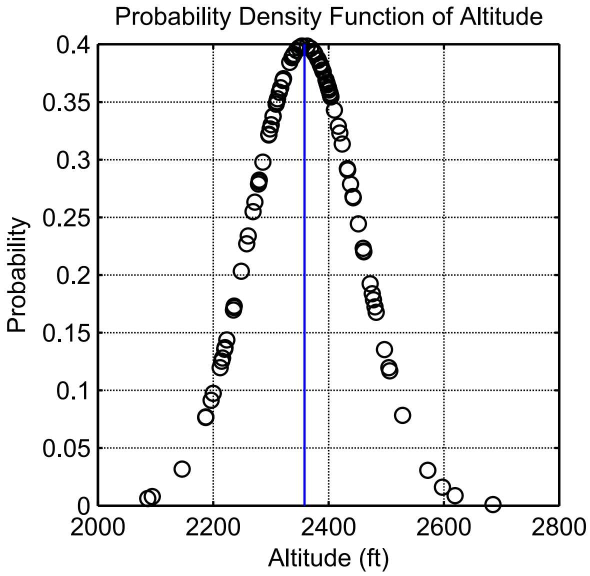


Fig. 7 Probability density function of altitude random variable.

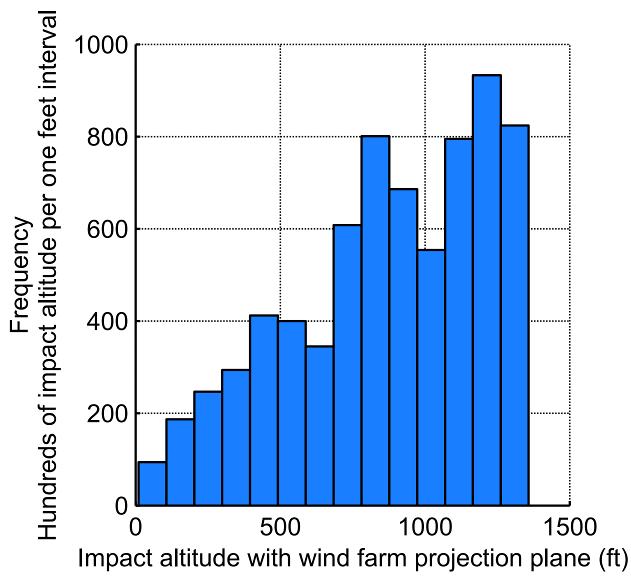


Fig. 9 Histogram of colliding trajectories with wind farm projection plane.

feasible population of 200000 simulations has been obtained. This is a sufficiently large set of engineering 'batch simulations' that were performed effectively with JSBSim by exploiting the parallel capability of Matlab computing software. The given values of ψ_{safe} were pursued exploiting the autopilot feature (heading hold) of the selected aircraft flight dynamics model (autopilot simulating a human pilot).

All simulated trajectories were scanned to find occurrences of collision with the wind farm. The collision events were detected by searching for those trajectories that intersect a given planar region. The planar region represents the wind farm frontal area with respect to the reference route. A visual sketch of this concept is depicted in Fig. 8 (see also Fig. 6).

For such a set of flight simulations a standard interpretation of probability definition can be applied (*frequentist probability*). Therefore, the resulting impact probability is calculated as the ratio between the number of colliding trajectories and the total number of the simulated trials.

The actual evaluation of the final CR is the result of a Monte Carlo analysis which has been divided in two successive phases. Initially a population of simulations is set up to find a *critical interval along the nominal course*, not considering the possibility to change the heading of the airplane after the engine failure. In other terms, only the random quantities (h_0, t_{fail}) are considered. The Monte Carlo study confirms the existence of a critical interval (this is also a result of the simplified approach of the previous section) and the outcome of the first phase is shown in Fig. 8. The histogram of colliding trajectories are shown in Fig. 9. In the first trial a number of 6623 collisions are found out of 100000 total generated trajectories. This leads to a probability of impact

$$P_{\text{NoTurn}} = \frac{6623}{100000} = 0.06623 \qquad (5)$$

In the second phase of the analysis only the critical trajectories of Fig. 8 are taken into account. In other terms, the escaping maneuvres — in chase of a heading ψ_{safe} — are those triggered by engine failures occurring when the airplane flies in the critical interval established in the first phase. The outcome of these trials is a set of colliding trajectories that defines an *angular critical interval*. A sample of these trajectories is shown in Fig. 10. In the second trial a number of 12922 collisions are found out of a second set of 100000 total generated trajectories. The probability of impact defined in this phase is

$$P_{\text{Turn}} = \frac{12922}{100000} = 0.12922 \qquad (6)$$

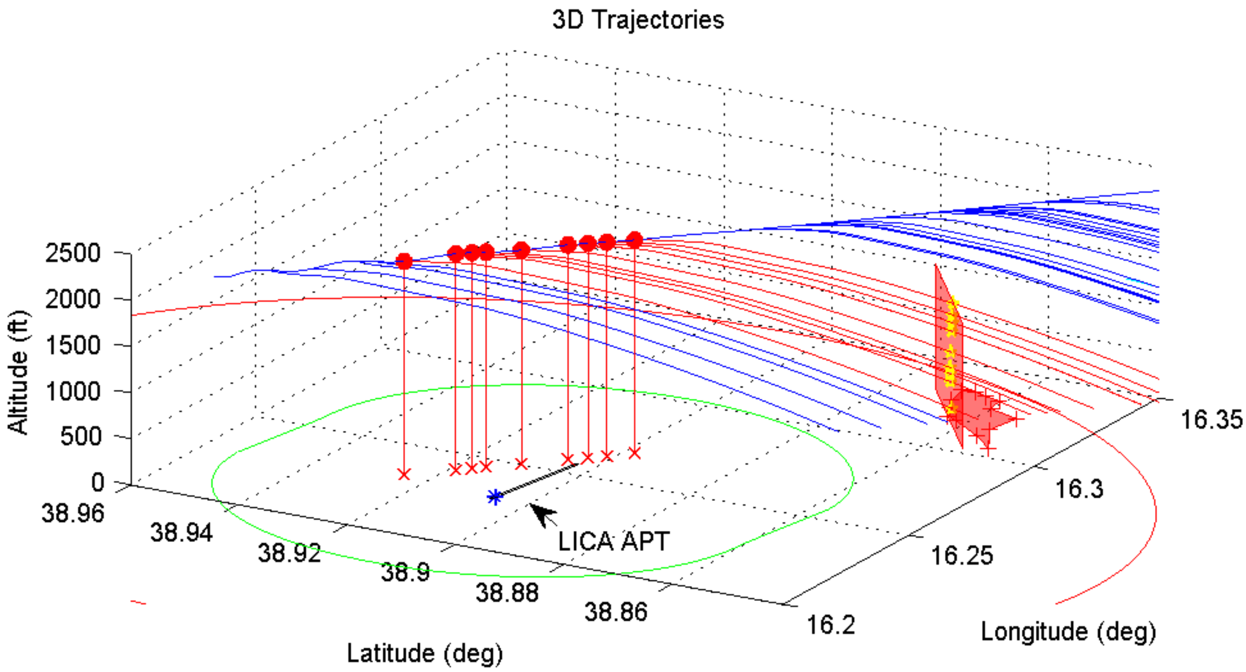


Fig. 8 A subset of trajectories generated with a Monte Carlo simulation (first phase, not accounting for deviations from the original heading). Red solid lines are flight paths intersecting a reference planar region and are flagged as impact events.

Combining the results (5) and (6) the probability P that the reference aircraft collides with a wind turbine of the plant after an engine failure is estimated as:

$$P = P_{\text{NoTurn}} \cdot P_{\text{Turn}} \cdot P_{\text{EF}} \\ = 0.06623 \cdot 0.1292 \cdot 10^{-5} = 8.558 \cdot 10^{-8} \tag{7}$$

This refined CR is very similar to (4). The result (7) is again compliant with the CRM acceptability threshold and confirms the validity of the simplified CR estimation approach.

6 Conclusions

Aeronautical studies are supportive tools to assess safety and regularity of operations around airports with ICAO non-compliant obstacles in place, such as those that violate the OLS. However, authorities do not provide any guidance on how to perform this kind of studies. This paper presents a methodology that may contribute to preliminary estimation of CR for wind farm siting and airports certification processes. The study proposed here improves a preliminary fully deterministic analysis with Monte Carlo simulations and the outcome is a refined CR assessment technique. The proposed approach is extendable to take into account other potentially critical events in a similar scenario.

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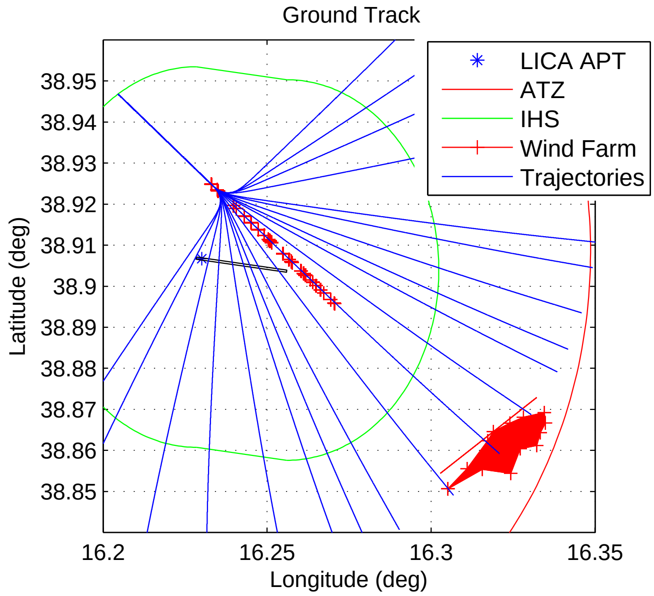

Fig. 10 Some of the trajectories generated with a Monte Carlo simulation. After a critical engine failure the pilot enters a turn in the pursuit of a safe final heading.

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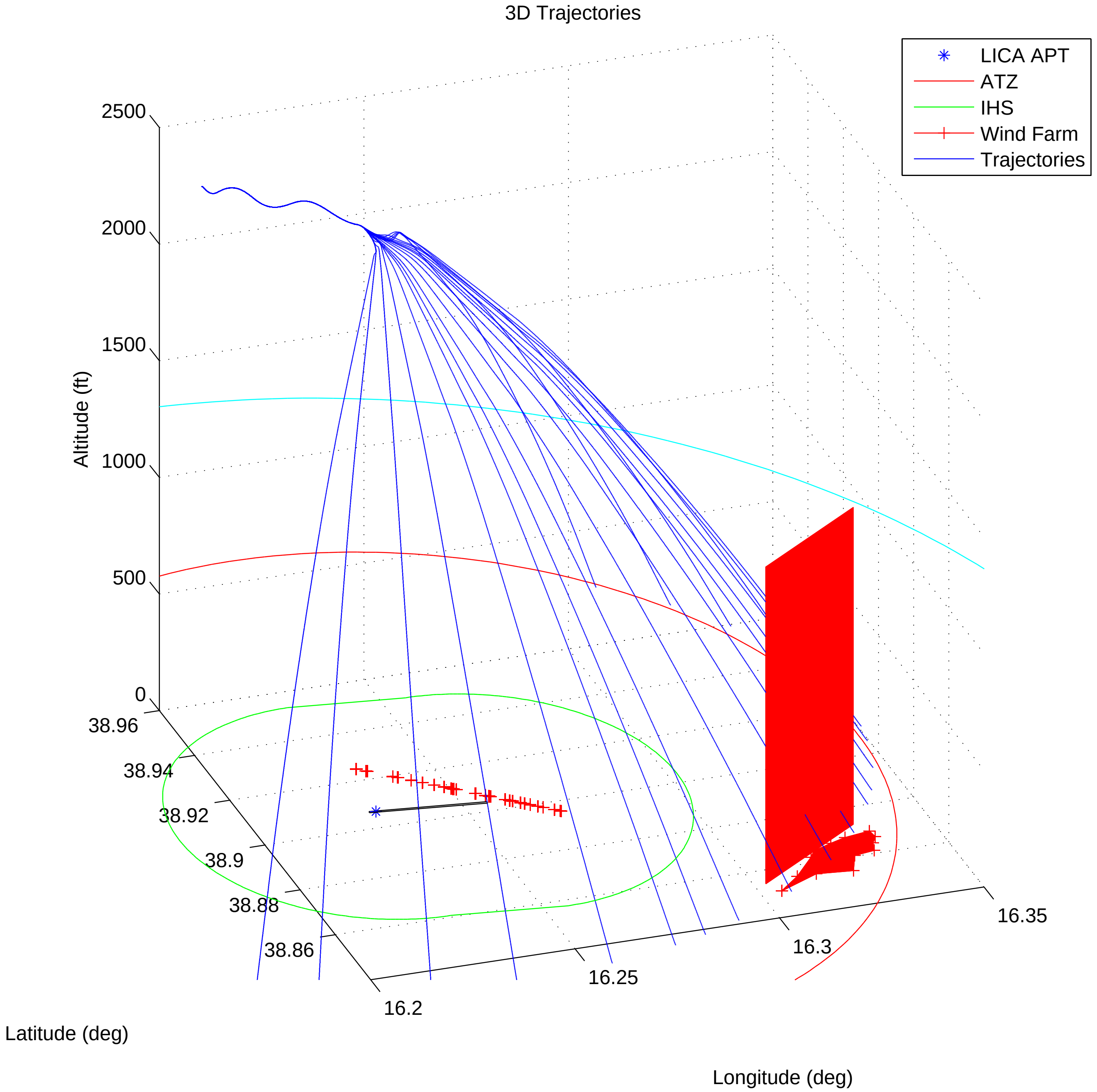

Fig. 11 A subset of the population of trajectories generated with a Monte Carlo simulation. Three dimensional visualization showing some flight paths intersecting a reference planar region.