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A Methodology to Assess the Safety of Aircraft Operations when Aerodrome Obstacle Standards cannot be met

An Application to a large close-in Obstacle at Frankfurt Airport's new Runway Configuration

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***Abstract*— When Aerodrome Obstacle Standards cannot be met as a result of urban or technical development, EASA in-line with ICAO allows proving an equivalent level of safety by carrying out an aeronautical study. However, detailed guidance in doing so is not provided. This paper aims at filling this gap with a proposed safety assessment methodology to value obstacle clearance violations around airports. It was applied for a safety case at Frankfurt Airport where a tower elevating 4 km out of threshold 25R violates severely obstacle limitation surfaces. The model refers to a takeoff and landing performance model (TLPM) computing precisely aircraft trajectories for both standard and engine out conditions at ground proximity forming the model's reference data: The generated tracks are used to estimate collision risk considering stepwise EASA/FAA, EU-OPS & ICAO clearance criteria. Normal operations are assessed with a probabilistic analysis of empirical takeoff / landing track data generating the local actual navigation performance (ANP) at site. The ANP leads through integration to collision risk for an aircraft with any obstacle. This step passed, the obstacle is tested for clearance within a "5-step-plan" against all performance requirements for landing climb, and takeoff climb. The methodology so delivers a comprehensive risk picture: The presented safety case for Frankfurt Airport showed an equivalent safety level despite the violation of standards: The collision risk during both normal and degraded performance operations was found to be still within ICAO Collision Risk Model (CRM) limits requiring only limited risk mitigation measures. The presented work should complement ICAO Doc. 9774 Appendix 3.**

Keywords - Aeronautical Study, Aircraft performance, obstacle clearance, Collision Risk, Engine-out operations

I. INTRODUCTION TO OBSTACLE CLEARANCE

Today's obstacle clearance criteria according to ICAO Annex 14 [1], PANS OPS Doc. 8168 [2], recently transferred into European law through the upcoming EASA CS ADR DSN [3], still refer on the 50 year old collision risk model (CRM). Meanwhile, aircraft (navigation) performance has however significantly improved [4], [5] so that today's obstacle clearance requirements may become too conservative: Estates around airports have become a scarce, valuable resource for industry suffering from perhaps over-conservative clearance requirements. Large airport projects such as new runways at Frankfurt; Vienna; Berlin or Munich airport demonstrate the conflict potential between urban planning and air traffic operator's interests. From a scientific standpoint, existing regulations for departure / arrival procedure design, obstacle clearance evaluation and collision risk determination do not show congruent requirements with only two "somehow usable" target levels of safety (TLS) values in place: the CRM TLS [6] valid for the precision approach segment ending at OCA/H (which is often far above the obstacle hot spots around airports) and the A-SMGCS TLS [7] valid during ground taxi, only. A systematic approach detailing specifically the valuation of non-compliant obstacles through an Aeronautical study as depicted in ICAO Doc 9774 Appendix 3 [8] is therefore crucial to make best land use around airports without hampering safe operations of aircraft. Also this approach should bring transparency into the various safety margin concepts as incorporated in the above standards.

The paper recalls existing guiding material for assessing the compliance of obstacles with clearance requirements in Section II, summarize the analysis processes for valuing obstacles against these requirements in Section III, presents the model built to assess the non-conformant obstacle induced collision risk for departing and landing aircraft while bridging the various clearance considerations under normal and critically degraded performance conditions (engine out, crosswind et al.) tackling flight mechanical and operational aspects in Section IV, and collects the findings of a safety case for Frankfurt Airport which was successfully investigated with the presented approach in Section V. Section VI closes with a vision on how the shown concept may complement ICAO / EASA recommended practices to foster a transparent, formalized assessment of non-compliant obstacles in the complex airport environment.

II. Obstacle Clearance Determination

Obstacle clearance is of relevance for runway design according to ICAO Annex 14 [1], and Doc ADM [9], for procedure design (ICAO Doc 8168 PANS OPS) [2], aircraft operation (EU-OPS) [10], and aircraft certification (EASA CS 25 [11] / FAR Part 25 Large Aeroplanes [12]). All these different requirements lead to given height margins above the ground respectively any obstacle (in fact vertical safety margins). They so implicitly dictate a level of safety against a risk of collision of the aircraft either with the ground plane or that obstacle. However, all three subjects refer to different geometric design standards and aircraft conditions. A safety model of Aircraft Operations when Aerodrome Obstacle Standards cannot be met will therefore have to consider all three subjects figuring out any discrepancies, and build either transfer functions or determine the most limiting case. They are recalled briefly in the next subsections.

A. *Obstacle Limitation Surfaces at runway design*

Based on ICAO Annex 14 und Doc 8168, a comprehensive set of standards and recommended practices has been internationally established. Centered on each Takeoff / Landing Runway, the ANC Obstacle Clearance Panel (OPC) defined limitation surfaces as early as in 1976 intended to protect aircraft in flight at ground proximity:

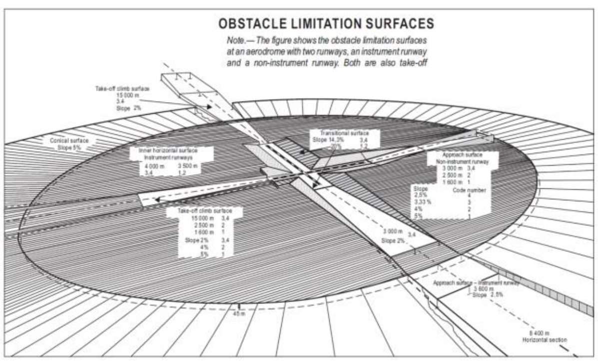


Figure 1. Obstacle Limitation Surfaces, Annex 14, Att B; p 313[1]

The design of these horizontal and inclined surfaces did obviously follow aircraft performance aspects (e. g. reference angle of climb / descent after takeoff / during final approach) by adding safety margins to the design path: An e.g. 5.2 % (equals 3.0°) design angle of descent during final approach is enveloped by the *approach surface* with a slope of 2.0% (1st section) to 2.5% (2nd section) inclination for a precision runway CAT I Code 3, 4 (Annex 14; Table 4-1,ch 4-8 [1]). Similar, the takeoff climb surface for a Code 3, 4 takeoff runway inclines with 2.0% so again inducing safety margins as aircraft typically climb with a gradient of 5% - 8%. To conclude, the OLS grant a certain, however unspecified maximum collision risk for aircraft providing a given navigation performance (ANP) operating on that runway. The following figure shows the currently given obstacle collision risk during a conventional ILS approach based on realistic ANP values [5]. It further highlights the gradients of ICAO's obstacle clearance surfaces OLS and OAS (which apply to precision approaches only):

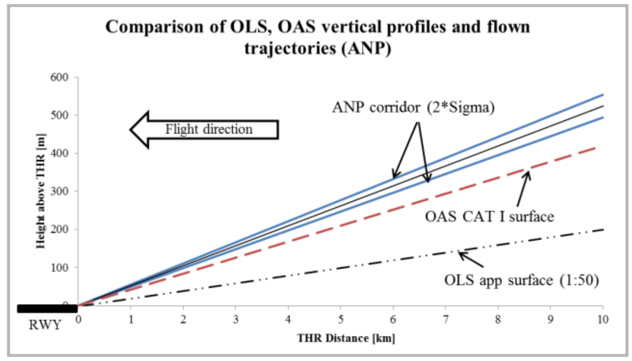


Figure 2. Heterogenous safety margins resulting from OLS and OAS (during approach)

As we assume regardless the chosen approach procedure an equal safety target level, the difference in altitude for both dotted lines can only consider additional "safety margin" necessary for operations with lower ANP e.g. for non-precision approaches (NPA) which will be subject to the following section I. B.

B. *Obstacle Clearance applied during procedure design*

Closely connected to the runway design, procedure design covers the detailed three-dimensional construction of approach and departure procedures to/from an instrument runway. For e.g. Code 3, 4 precision instrument runways, usually a large set of alternative procedures are being developed to fulfill environmental (noise abatement), operational (direct routings), safety aspects (e.g. non precision approaches offered as contingency procedures) as well as the consideration of in- and outbound traffic flows being geographically dispersed.

With regard to precision or APV approaches, ICAO Doc. 8168 [2] dictates the consideration of Obstacle Assessment Surfaces (OAS) consisting of inclined surfaces referenced to the threshold of that runway, looking similar to the OLS with a less conservative character (see Figure 2) but extending into the missed approach (not shown): Two alternative safety conclusions when comparing OLS versus OAS can be drawn: Either the OLS allows lower ANP to methodologically cover also NPA (as derived in section I.A) with the OAS laying above the OLS or a different level of obstacle collision risk is implicitly accepted. Consequently, safety assessment will have to include all obstacle related procedure surfaces extending to the visual (approach) segment surface (VSS), the outbound obstacle identification surface (OIS) and the on-following takeoff funnel. The VSS prolongs the OAS from the Obstacle Clearance Altitude/Height (OCA/H) down to the ground plane, assuming only visual guidance capability for the cockpit crew leading to lower ANP. As the OCA/H itself is also specific for each procedure and does depend from the obstacle situation, the whole design process takes potential for closed loop configurations (obstacle drives OCA/H and so the length of the VSS). So we can conclude, that the OAS, other than the OLS, are not only representing significantly differing CR values but that they also allow for two different design concepts: either determining those obstacles to be considered in the calculation of the associated OCA/H to the procedure[1] or once set, refuse further adoptions induced by new obstacles by just interpreting OAS as obstacle limitation surface (which de facto is often the case). The ICAO Collision Risk Model (CRM) [6] as introduced in the 70ies however does not cover the testing of these different design options – it only considers the OAS as an approximated 10^{-7} per operation collision iso-risk line neglecting time and PA procedure specific aircraft ANP figures. The presented assessment will also have to overcome this (second) deficiency.

For departures, consideration includes aside the OLS the OIS extending from the DER with a 2.5% inclination and to be compared to the Procedure Design Gradient (PDG) for each procedure. To know the local CR considering all so identified obstacles, we have to refer to the local ANP ideally specific for each procedure during both normal and also during "abnormal" conditions assuming one engine inoperative (OEI) conditions to also cover rare but safety critical occurrences for the risk estimation.

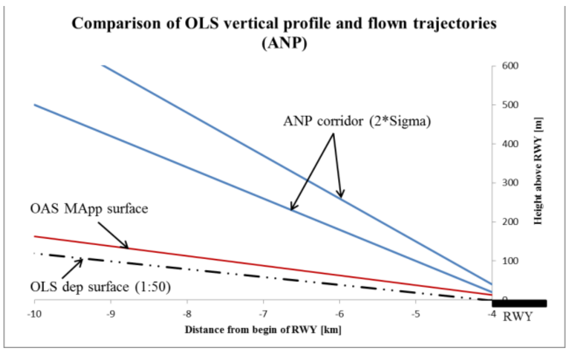


Figure 3. Heterogenous safety margins resulting from OLS and OAS (departure)

C. *Aircraft Certification*

The various surfaces (OLS, OAS, VSS, and OIS) analyses have in common the assumption that aircraft operate at normal performance conditions. Certification of aircraft according to FAA Part 25 [12] resp. EASA referring to CS-25 [11] however takes additionally degraded, OEI performance test cases during takeoff, final approach and landing climb into consideration: The aircraft so must be accelerated on the ground to the engine failure speed v_{EF}, at which point the critical OEI condition begins, lasting for the rest of the take-off (EASA CS-25.109 / CS25.111 ff. [11]). The takeoff section ends, the climb phase begins at 35 ft (jet aircraft, 50 ft prop aircraft) above the takeoff surface at the end of the takeoff distance (15ft for wet runways). From there on, the aircraft must demonstrate its climb performance as so-called gross flight path which will be diminished by aircraft type specific climb gradient reductions generating yet another safety margin: e.g. 0.8% for two-engined aircraft along the takeoff flight path. No evidence is given so far for the correlation to the safety impact of that regulatory requirement. A comprehensive safety assessment will also have to tackle this (third) aspect.

To conclude: All certified aircraft must demonstrate their certified required takeoff, landing distances and climb out performance. A second branch of test cases for obstacle clearance will have to be considered aside those tackled in the first and second bunch of clearance considerations: degraded aircraft performance combined with unfavorable ambient conditions like crosswind. These effects can best be handled by defining hazard scenarios in which the aircraft must prove obstacle clearance in terms of e. g. demonstrating minimum climb performance.

The following Sections III and IV present the concept for a Safety Assessment (SA) aiming at satisfying all of the above requirements thus bridging these different requirements coming from airport planning, procedure planning and certification of aircraft so generating a transparent and homogeneous risk picture.

III. Analysis of non-compliant Obstacles

When conducting the SA, we start with systematically spotting for obstacles in the vicinity of the runway system being candidate to violate one of the clearance criteria as presented in Section II. This process is not executed obstacle by obstacle but by limitation criteria starting from the most stringent to the less ones with reference to Figure 2 and 3. Respectively, the following process forms the hazard assessment phase of the SA:

A. *Apporach and Takeoff OLS Investigations*

Independent from specific aircraft performance criteria, EASA generally requires OLS considerations as follows: *" means a series of surfaces that define the limits to which objects may project into the airspace around aerodrome to be* ***ideally maintained free*** *from obstacles"* [3]. Of course, we can convert these surfaces into performance criteria and so determine the implicit climb / descent requirement:

$$\tan\gamma = 1/50 = 0.02 \text{ (OLS dep/arr surface gradient)} \quad (1)$$

$$\gamma_{OLS} = 1.145° \quad (2)$$

Regardless any obstacle clearance considerations, we can calculate the minimum climb gradient and minimum rate of climb (and descent) ROC/ROD as follows for the given low altitude and small climb angles:

$$ROC/ROD_{min\ OLS} = TAS \sin\gamma_{min\ OLS} \approx CAS\ \gamma_{min\ OLS} \quad (3)$$

For a typical final approach (v_{REF}) resp. climb out safety calibrated airspeed (v_2) of 150 kt, this leads to a ROC/ROD_{minOLS} = 300 ft/min, proving a very conservative safety character of the OLS surfaces, equaling very low safety requirements as it will be shown in Section IV.

[1] Obstacle clearance altitude is referenced to mean sea level and obstacle clearance height is referenced to the threshold elevation or in the case of non-precision approaches to the aerodrome elevation or the threshold elevation. ICAO Doc. 8168, Vol. II, Section I-1-1-6 [2]. Beyond the OCA/H, the approach surface is being extended by a Visual Approach Surface (VSS) assuming reduced aircraft ANP as guidance is formally limited to visual cues.

B. Approach and Missed Approach OAS Investigations

As shown in Figure 2. for a given ANP distribution along the flight track, the OAS are less conservative than the OLS however equally do not consider specific aircraft performance categories but solely the PA category, localizer location and further system related parameters. For keeping those surfaces free of obstacles, the following vertical flight path requirements for a typical ILS, CAT I, 3° glideslope OAS result:

$$\gamma_{\text{App OAS}} = -1.62° \quad (4)$$

$$\gamma_{\text{MissedApp OAS}} = 1.43° \quad (5)$$

Which leads with (3) to:

$$ROD_{App} = 430 \text{ ft/min} \quad (6)$$

$$ROC_{MissedApp} = 380 \text{ ft/min} \quad (7)$$

The higher gradient values in equations (4) and (5) show the usefulness of the chosen process. It should however be noticed, that in few cases for very close-in obstacles; the OAS may formally be more restrictive than the OLS, however in those few cases the OLS prevails (PANS-OPS Volume II Part III Attachment B [2]).

C. The role of the Obstacle Clearance Altitude

The final instrument approach ends and the missed approach segment begins at the OCA/H: The higher the value, the earlier the pilot needs visual contact to the runway to continue landing. Non-precision approaches with OCH >= 600 ft so suffer limited usability due to insufficient visibility and ceiling for the sake of safety. With regard to CR, we may further notice that the OCA/H induces far more conservative safety margins as for PA with up to 250 ft clearance for close-in obstacles in the primary area compared to 35 ft for takeoff (see above). The OCA/H as third test case gains further complexity as it must be calculated for each (stall speed related) aircraft category [13]. Finally, we may further take into consideration As obstacle typically are closer to the runway then where the OCA/H is being reached, this test case is sequenced at third position.

D. Net Flight Takeoff Path Analysis

During type and aircraft specific certification, the aircraft has to demonstrate landing climb, takeoff and climb out performance now under both normal and degraded conditions. This demonstrated performance will potentially limit its operational capabilities in terms of maximum allowable masses, payload, and range. E.g. if a given climb gradient or a declared distance cannot be met, takeoff mass (as fuel or traffic load) must be reduced and will limit profitability of the flight. This process is driven by the parameter weight (W), required Thrust (T), Power (P) and selected climb out safety speed (v_2), as this one triggers climb performance as shown in equation (3). T and $v_2$are coupled at constant speed through:

$$T = \frac{dm_{Air}+dm_{Fuel}}{dt} v_{EG} - \frac{dm_{Air}}{dt} v_2 - K \; and \; \sin\gamma = \frac{T-D}{W} \quad (8)$$

$$P = T * v_2 \; and \; v_2 * \sin\gamma = ROC = v_2(\frac{T-D}{W}) \quad (9)$$

EG = exhaust gas, K = pressure effect forces, D = Drag

Equation (8) shows the linear correlation of climb gradient (CG) and weight, equation (9) the respective linearity between operating speed and ROC/ROD. Along the takeoff flight path, the “2nd segment” implies the highest CG. Obstacles must be overflown with 35ft clearance. As climb-out profiles are more inclined, obstacle limitations likely become limiting in the approach and landing phase. Independently, we again can determine a minimum clearance requirement resulting from procedure design similar to the process in section III.A: with the procedure design gradient (PDG) [2] at 3.3% (OIS gradient of 2.5% plus 0.8% safety margin) we equally can calculate a ROC for a given climb out speed v_2:

$$\gamma_{\text{Dep}} = 1.89° \quad (10)$$

with v_2 = 150 kt we come to ROC_{DEP} = 500 ft/min (11)

The slightly higher ROC values in (11) compared to (7) argue to rank this test to this subsequent position. Figure 4 depicts the additional safety margin versus Figure 2 and 3 resulting from the 35 ft clearance requirement reducing the CR provided the same ANP value and distribution (shown below as sketch):

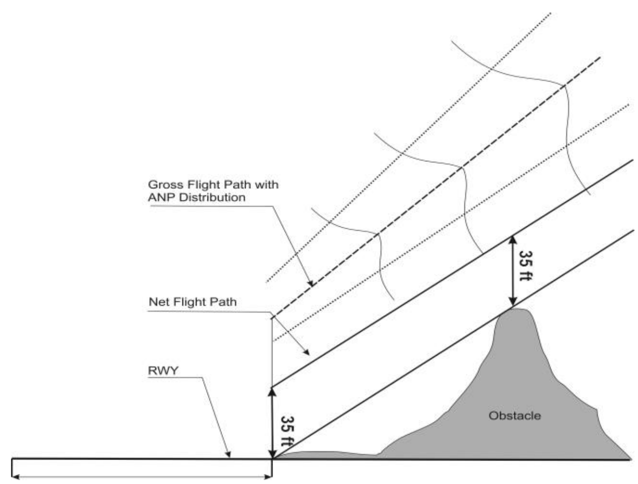


Figure 4. Additional Obstacle clearance and required net flight path corrrections resulting in lower CR as for OLS and OAS

With today’s economic pressure in the ATM System, limitations for takeoff mass are hardly acceptable especially at large (Code 3, 4) airports. As such, the safety test case will usually be performed with maximum structural takeoff and respectively landing masses considerations.

It shall be noticed, that this fourth step also holds some complexity, however it does not consider – compared to step three – detailed stall speed dependent aircraft categories but a simplified threefold concept only relying of the number of engines (2, 3 or 4) installed. An obstacle so becomes only relevant, if the respective CG requirements are not met leaving a 35ft clearance above the object. The clearance surface can so be represented by the inclined (net flight path) surface reduced by 35 ft.

Section IV now incorporates this analysis concept and adds systematic algorithms to the presented analysis forming the SA.

IV. SAFETY ASSESSMENT METHODOLOGY

A. *Legitimation*

A general philosophy of handling exceptions from the presented standards has been adopted by ICAO[2] in Doc. 9774 [8] and significantly opened recently by EASA in CS-ADR DSN [3]. Accordingly, a so-called Aeronautical Study can be applied as Acceptable Means of Compliance for certain violations such as obstacles conflicting with the large horizontal obstacle limitation surface. Explicitly, ICAO states *„An aeronautical study is a study of an aeronautical problem to identify possible solutions and select a solution that is acceptable without degrading safety"* [8]. As such, supervisory authorities in ICAO member states are generally allowed agreeing with ICAO non-compliant constellations or procedures as long as such study proves an equivalent safety level. However, there is no specific guideline given by the ICAO how to conduct these safety assessments.

Therefore, the main goal of the presented methodology is to design a uniform concept for obstacle approval verification clearly having in mind the implicitly deferring safety margins as presented in Section II.

B. *Architecture*

In line with Eurocontrol's SAM [14], an Aeronautical Study shall comprise the following main sections: Hazard Assessment and Safety Risk Analysis including potentially risk mitigation.

The main hazard to be assessed here is very simple: The collision with any formally non-compliant obstacle according to Section III.

For the Safety Assessment Analysis, the following architecture has been built two consider that (main) hazard comprehensively with the findings of Section II in mind:

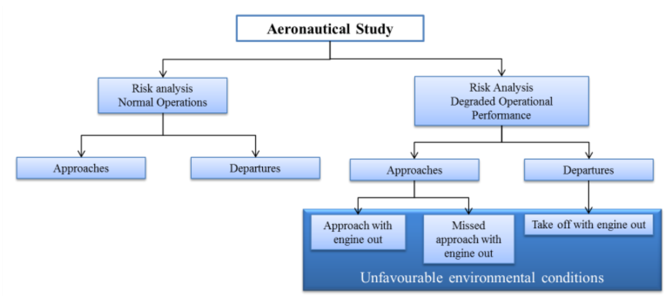


Figure 5. Model Architecture of safety assessment methodology

As shown, the model comprises two main components, the analysis of <u>normal operations</u> and of quite rare but safety critical, <u>degraded operational performance</u> (emergency related operations).

[2] *"**.New objects** or extensions of existing objects should not be permitted above the conical surface and the **inner horizontal surface**.....except when, in the opinion of the appropriate authority, an object would be shielded by an existing immovable object, or after aeronautical study it is determined that the object would not adversely affect the safety or significantly affect the regularity of operations of aeroplanes*." [1]

Normal operations are flight procedures compliant with the standard operational procedures (SOP) as published for the specific aircraft and following the ATC clearances as filed and expected. As such, also a takeoff with one engine inoperative is basically a normal operation, whereas the same takeoff e. g. leaving the cleared departure route (SID) for unspecified reasons is considered as emergency operation. For safety considerations, emergency operations always assume a degraded performance aircraft behavior when assessing the effects to the declared hazard.

1) *Normal Operations*

Normal operations represent statistically more than 99% of all operations at large (Code 3, 4) airports. The Normal Operations model (NOM) processes historic aircraft track data from departures resp. arrivals at the investigated airport for a significant time period (typically 6 months) gathered from radar or multi-lateration sensors. Similar to the ICAO CRM methodology [6], the real track data will be compared to the defined track data and modeled as offset probability density functions (PDF). The PDF concept has also been adopted by ICAO with their RNAV/RNP or PBN documents [15].

We could prove in [5], that for all cases studied, aircraft navigation performance behaves normally distributed. Nonetheless, we let the NOM start again with first only *assuming* two dimensional (y as cross track reference, z as vertical reference) Gauss PDFs, f(y), f(z) with a 2 σ value as procedure level of quality identifier (e.g. RNP 0.3 for a non-precision approach procedure equals a square root variance of 0.3 NM left and right to the desired flight path for 95% of the flying time) [15], analytically described at each location along the flight track as shown in equation (3) for the cross track plane y:

$$f(y) = \frac{1}{\sigma_y\sqrt{2\pi}} e^{-\frac{(y-\mu_y)^2}{\sigma_y^2}} \qquad (8)$$

So y and z represent the track coordinates as sampled, the mean with μ and its variance with σ^2. It shall be noticed, that along track considerations are unnecessary in the given context since CR is considered as time independent.

After verifying the assumption of normality of the track data by means of chi-squared tests along the flight track, a Grubbs' test is applied to detect potential outliers: Grubbs' test detects one outlier at a time: Each potential outlier is expunged from the dataset and the test is iterated until no (more) outliers are detected. Along the defined takeoff or approach path, vertical cuts through the cross track plane provide insight into the shape characteristics. This methodology has already been effectively applied in [5]. Following the normal distribution, mean and standard deviation reflect graphically center and height of each "bell" curve (see Figure 6).

The NOM systematically integrates the local PDF to a dedicated obstacle distance both vertical and lateral at the abeam location along the flight path to calculate the local CR for that object. The Collision Risk per movement can then be compared to a pre-set TLS such as the ICAO CRM TLS, as shown in the following figure for the lateral plane with different iso-risk contours ($1*10^{-3}$, $1*10^{-5}$, $1*10^{-7}$, and $1*10^{-10}$).

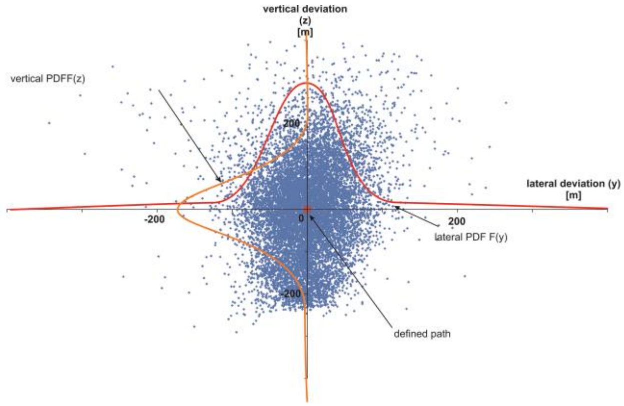


Figure 6. Normally distributed track offsets around the flight path

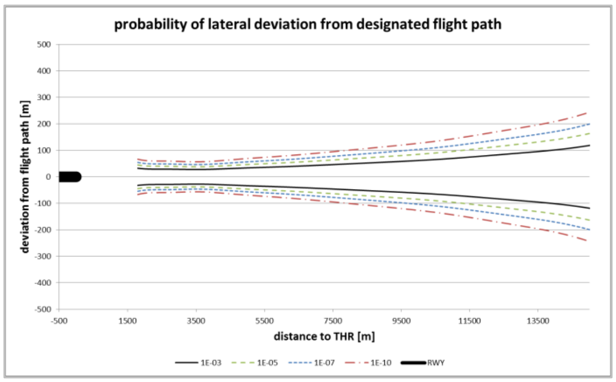


Figure 7. Probability of lateral deviation from designated flight path or risk to hit an objstacle with CR(z) =1 in lateral plane

By extending the integration boundaries accordingly, the CR can also be calculated against the ground plane or any height above ground to estimate a ground / height projected risk contour enveloping the flight path laterally. It may however be noticed, that close to the ground, track data typically hold remarkable unreliability due to radar beam refraction and multi path phenomena, which should be overcome by applying multi-sensor strategies such as additionally using multi-lateration track data. Aside these sensor aspects, the NOM allows safety comparisons of any procedural obstacle clearance standard.

Accordingly, the following TABLE I collects the computed risk levels using ANP from [5] at a preselected height above ground for the OAS and OAS (CAT I) approach surfaces.

TABLE I. COLLISION RISKS FOR DIFFERENT APPROACH SURFACES, RELATED TO 3° GLIDE PATH AND ANP

Distance to thres-hold [m]	**Height of the 3° GP**	**PROBABILITY TO UNDERCUT A DEFINED SURFACE**			
		calc. sigma vertical	***Surface***	***Height of the surface***	***calc. Collision Risk***
1.000	67.6 m	7.4 m	OLS	18.1 m	1.8E-11
			OAS (CATI)	20.5 m	8.3E-11
2.000	120.6 m	8.5 m	OLS	38.8 m	6.6E-22
			OAS (CATI)	49.0 m	3.3E-17
3.000	172.5 m	9.6 m	OLS	58.8 m	2.2E-32
			OAS (CATI)	77.5 m	3.4E-23

TABLE I clearly shows the **different implicitly (ICAO) accepted CR** if we start from identical ANP values: The target CR so varies between $2.2*10^{-32}$ to $2.2*10^{-23}$ at a 3.000 m distance to the runway location. This difference is going even higher for larger THR distances. The NOM so proves to be crucial for generating a comprehensive obstacle clearance risk picture.

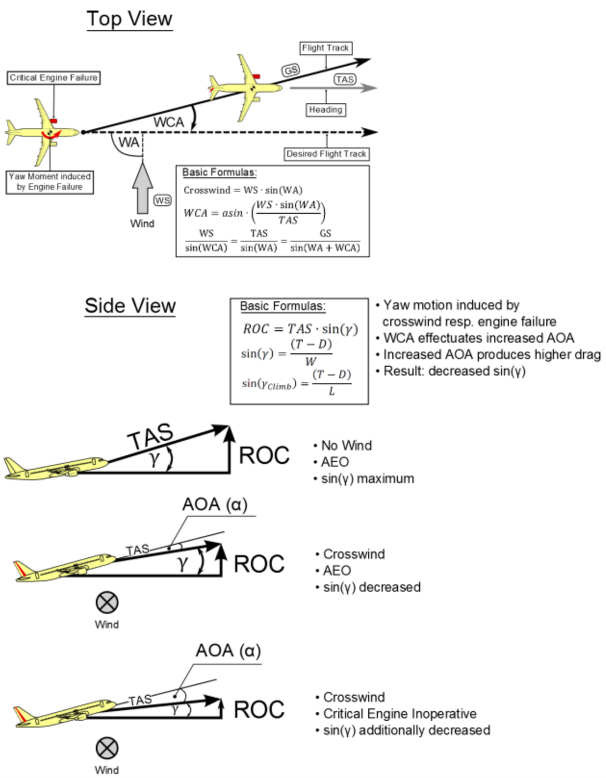
Of course, the ANP distribution may (slightly) vary depending on the (time dependent) environmental conditions or well differing procedures (e. g. a conventional straight-in PA vs. a more innovative segmented NPA. However, such differing ANP distributions do not alter the general conclusions drawn here, as we could show in [16].

2) Degraded Operational Performance

The degraded operational performance model (DOM) considers those effects of the remaining empirically less than 1% traffic operations in emergency or unspecified conditions, not following normal procedures according to SOP. Those rare events however suffer a significantly increased collision risk resulting from flying un-cleared procedures combined with – what we assume here - reduced performance capabilities of the aircraft resulting from an engine failure as reference safety case for a degraded performance of the aircraft during takeoff or landing climb.

From a statistical perspective, the DOM looks specifically at the (far) tails of the normal distributions used in the NOM: These tails cover only a few percent of all track data (<0.3% for a 3 Sigma threshold), their functional approximation so holding remarkable unreliability. To overcome this weakness, the DOM revert to a scenario technique representing these seldom cases on a functional level allowing to deterministically analyzing a collision potential ("will pass or the obstacle or not").

Regardless the technical, meteorological or human factors related *causes* leading to these scenarios, the DOM computes the *effect* of degraded performance while additionally assuming unfavorable operational conditions such as a strong cross wind coming windward with respect to the remaining engine(s) still operative. This constellation increases at max the required wind correction angle (WCA, see Figure 8.) thus degrading the lateral / vertical aircraft navigation performance.



AOA = angle of attack, WA/WS =wind angle/speed, AEO = all engines operative

Figure 8. Underlying flight performancein the DOM

This model is applied to all three constellations while assuming the most critical engine out case few seconds ahead of passing the non-compliant obstacle:

1. Approach with two different settings (flaps extended, gear up) and landing configuration (flaps high/full, gear down)
2. Missed Approach (at FAF as default)

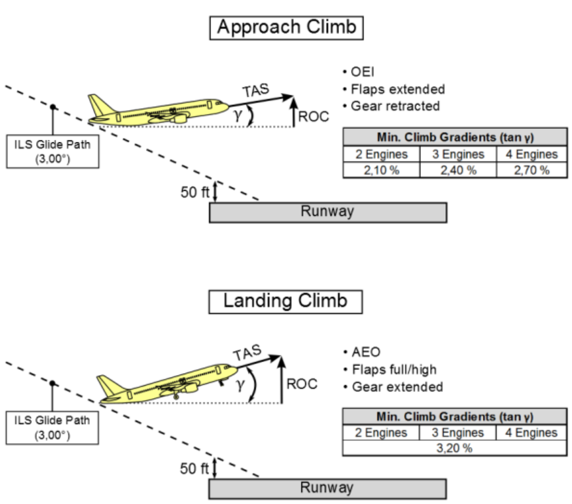


Figure 9. Worst Case Analysis for Approach and Landing Climb obstacle clearance: Approach/Landing configuration impact on ANP and Rate of Climb

3. Takeoff (at v_{EF} as default) with two different flap/slat settings to weigh-in corresponding CG and ROC effects on obstacle clearance. It minimizes these effects according to the following generalized aerodynamic effects:

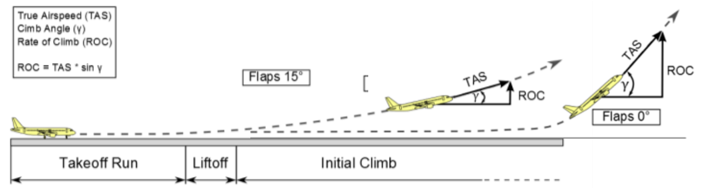


Figure 10. Lowest pass altitude analysis for takoff obstacle clearance

The Takeoff and Landing Performance Model (TLPM) which evolves from the EJPM [17] is being used to calculate the resulting 3D tracks for all DOM scenarios. Validation was also performed with licensed flight planning software [18].

The presented threefold flight performance analysis was embedded into a five-step evaluation scheme as follows:

DOM Step 1: Vertical Performance Analysis

Step 1 determines the vertical obstacle clearance by applying minimal vertical performance requirements according to EASA CS-25 for each scenario which does contain the formulation of a "direct to" trajectory with the obstacle. It answers the following question: *"Based on purely vertical certification requirements: Does all aircrafts overfly the obstacle safely even if though a direct trajectory towards the obstacle is assumed (regardless the aircrafts capability to fly this horizontal trajectory)?"*

For a positive result (the answer is *yes*) for all scenarios, considering all aircraft performance types relevant to the airport, the DOM analysis completes at this step 1. Elsewise, we continue as follows (this is consecutively true for all on-following steps):

DOM Step 2: Procedure Design Analysis

Step 2 additionally contains lateral consideration of the obstacle with respect to all existing approach/departure procedures and their respective clearance requirements according to EU-OPS 1 [10] and ICAO PANS-OPS [2]. Therefore the question of step 2 is:

"Does the obstacle violate any departure or approach procedures clearance requirements?"

DOM Step 3: Lateral Performance Analysis

Step 3 additionally considers based on the trajectory resulting from step 1 (vertical) and step 2 (lateral) both additional lateral and vertical divergences from the intended route during approach or departure resulting from OEI and adverse wind assumption. Step 3 uses the TLPM to compute these critical trajectories to answer the question of step 3:

"Is the obstacle's location critical even if we assume OEI and adverse wind conditions?"

DOM Step 4: Lateral Flyability of the critical trajectory

Step 4 investigates the fly-ability of that trajectory found to be most critical in step 3 through consideration of performance aspects laterally: maximum bank angle with flaps extended leading to limited turn radii. Step 4 so answers the question:

> *“Is the developed most critical trajectory flyable at all in terms of flight performance and flight mechanics?”*

DOM Step 5: Vertical Performance Analysis of the critical trajectory

Step 5 investigates into the aircraft’s vertical flight profile as fixed in step 4 considering OEI yaw momentum induced drag leading to generally degraded CG values (see also Figure 8.). The question to be answered in this step can be concluded as follows:

> *“Are aircraft flying the most critical trajectory able to ensure sufficient flight altitude to cross the obstacle safely?”*

Often, step 5 concentrates on identifying aircraft classes with relatively poor climb performance (such as e.g. light twin engine prop aircraft or heavy aircraft such as A340).

With these fife steps, the DOM so covers all effects resulting from adverse conditions resulting in a collision threat, not covered by the NOM.

This SA methodology was already applied for several safety cases in Germany. Section V reveals such application for demonstration and verification purposes.

V. Safety Case Close-in Obstacle at Frankfurt Airport

A. Environmental settings

As stated in Section IV.A, the hazards, here the obstacle subject to investigation need to be located relative to the runway system of Frankfurt Airport (FRA): We focus on an 80m tower building located 600 m ahead of threshold 25C and 1,100 m across its extended centerline, close-by the extended centerline of Frankfurt’s new landing runway 25R:

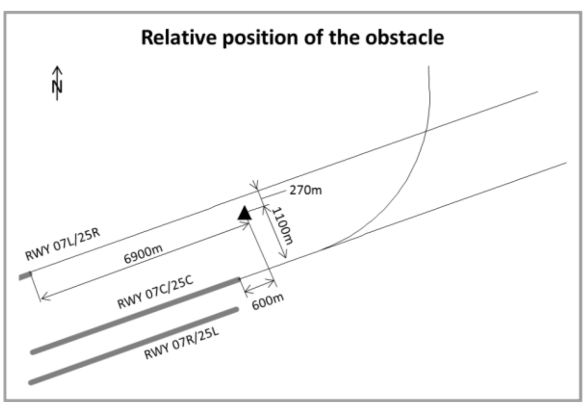


Figure 11. Location of the critical obstacle - the safety case EDDF

The obstacle clearance analysis with regard to the OLS of all relevant RWY directions proved a violation of the horizontal surface of the center RWY 25C/07C and of the south RWY 25L/07R. None of the OAS was however violated:

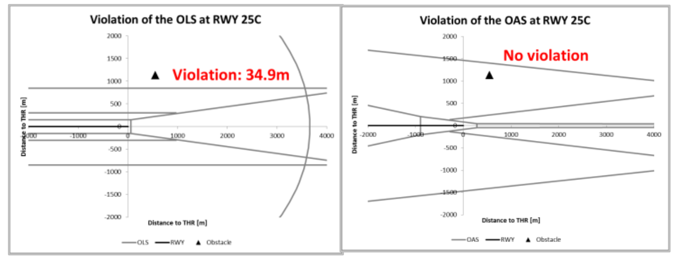


Figure 12. Exerpt of the Obstacle Clearance Analysis for the runway 07/25C, OLS – left figure, OAS CAT I – right figure

B. NOM Application

Flight track data for a 6 month period at FRA was used for the ANP analysis preceding the CR calculations [19].

1) Outbound Traffic Analysis

All departure routes passing nearby the considered obstacle operating from runway 07C were analyzed (07R routes are farer away, 07L/25R allows landings only). As shown in Figure 13, flight tracks of the northbound departure route (SID) BIBTI 3E were identified as the most relevant one:

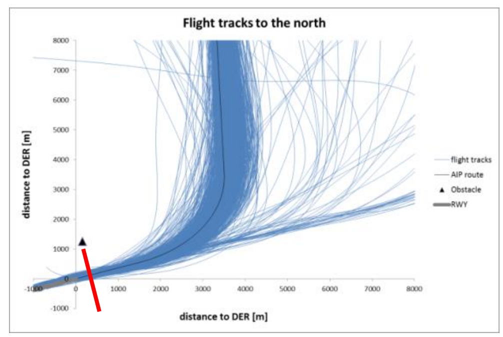


Figure 13. FRA Flight tracks for runways in use 07, outbounds, FANOMOS Data, with obstacle critical cross section (red line)

The relevant cross section (the normal plane to the route through the obstacle) was found almost in the straight out segment of BIBTI 3E, at 600m beyond DER. Following Figure 14 shows the route specific flight track’s distribution at this cross section (BIBTI 3E in red, all other departures in blue):

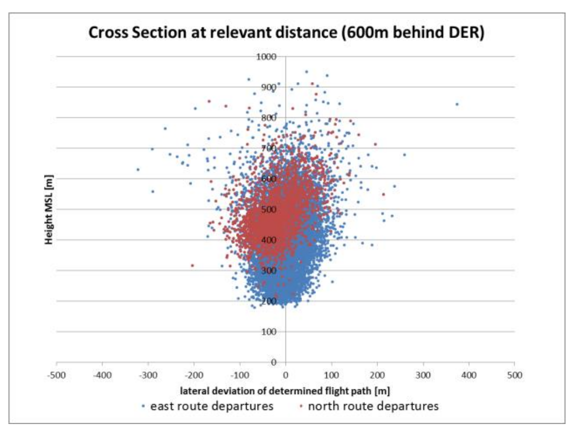


Figure 14. Relevant Cross Section passing through the critical obstacle, at 600m DER distance, departures from runway 07C

Figure 14 clearly shows a tendency for aircraft on BIBTI 3E to climb faster following a required PDG of 6.3% than other traffic. They further already initiate turning to the north (more located to the left in the figure) compared to the other traffic.

The SID specific ANP analyses were then performed along the statistical methods as explained in Section III. Following Figure 15 shows the determined ANP values and resulting CR iso-risk lines for departing aircraft on BIBTI 3E and all other routes:

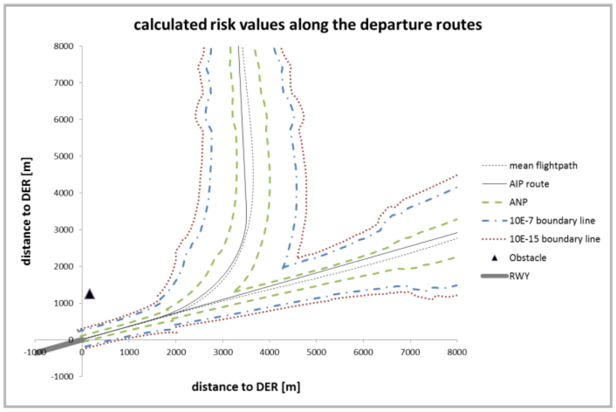


Figure 15. Iso-risk lines and ANP values, outbounds on runway 07C

The poorest ANP values (XTT and VTT) per class of aircraft and per route were identified as depicted in TABLE II. It also shows the probability density function's (PDF) shape parameter before / after the critical 600m cross section:

TABLE II. STATISTICAL PARAMETER ALONG THE FLIGHT TRACK (CRITICAL CROSS SECTION HIGHLIGHTED IN GRAY)

Distance from DER [m]	VERTICAL		LATERAL	
	Sigma [m]	*VTT [NM]*	*Sigma [m]*	*XTT [NM]*
400	85.0	0.092	43.5	0.047
500	85.9	0.093	44.8	0.048
600	86.6	0.094	45.7	0.049
700	87.2	0.094	46.7	0.050
800	87.9	0.095	47.7	0.051

The double integration of the PDF both vertically and laterally to the obstacle equals the specific CR per takeoff:

TABLE III. CALCULATED COLLISION RISK FOR DEPARTUERES

Collision Risk		
Lateral (XTT)	**Vertical (VTT)**	**Per departure**
2.10E-115	1.97E-02	4.13E-117

Due to the position of the obstacle at 600m from DER, the CR VTT value is relatively high with $1.97*10^{-2}$ per departure, whereas the XTT related CR is – at a lateral offset of 1,100m for the obstacle from the route - negligible with values below $1*10^{-100}$ per departure, resulting in an overall collision risk of $4.13*10^{-117}$ per departure.

2) Inbound Traffic Analysis

For approaches, both north and center runway are relevant. Applying the same investigation steps as for the departures, we computed, compared to the outbound case, clearly higher ANP values as expected with 99% of all aircraft performing ILS approaches. This leads to respectively smaller CR figures below $1*10^{-117}$. The furthermore calculated CR via ICAO's CRM [6] showed as well a negligible CR outside the calculation limits of the CRM program (< $1*10^{-15}$ per approach).

Concluding, for the normal operations at Frankfurt Airport we could prove a collision risk for takeoff and landing below ICAO's TLS at $1*10^{-7}$ per operation. The calculated CR below $1*10^{-100}$ shows both the necessity for scenario based risk analyses as provided with the DOM and a re-validation of ICAO's CRM.

C. DOM Safety Case Application

1) Scenario set-up

Based on the obstacle's location as shown in section V.A the following DOM hazard scenarios were identified:

1. Approach RWY 25R
2. Missed Approach RWY 07L
3. Missed Approach RWY 07C
4. Takeoff RWY 07C

The following Figure 16 depicts all four scenarios:

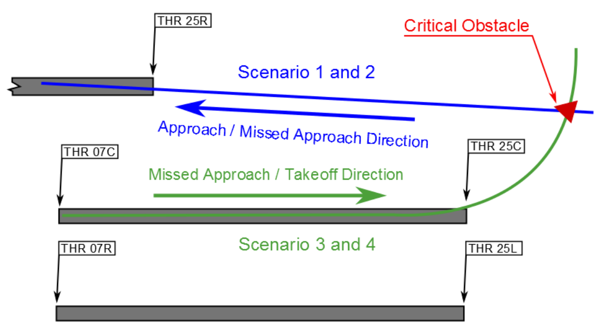


Figure 16. Identifed DOM hazard scenarios – safety case FRA

All operations on runway 25L/07R and runway 18 were excluded from the investigation as explained in section V.B.

2) DOM Step 1: Vertical Performance Analysis

Applying the minimum climb requirements according to CS-25 we can prove compliance for scenarios 1, 2, and 3. Scenario 4 "Takeoff RWY 07C" does not pass the evaluation. TABLE IV shows the obstacle conflicting profiles for multi-engined aircraft (negative values indicate a flight path below the highest point of the obstacle):

TABLE IV. VIOLATION ALTITUDES SCENARIO 4

Scenario 4 - Obstacle clearance [m]		
2 engines	3 engines	4 engines
-46.10	-40.00	-33.90

Consequently, we declare all scenarios but this one as non-critical - scenario 4 is subject of further investigation along step 2 to 5.

3) DOM Step 2: Procedure Design Analysis

In this step, three separate phases will be passed:

Phase 1: *Analyze the most critical departure route*[3] *along EU-OPS 1.495 standards.*

Results: The examination revealed that the obstacle does not penetrate the "takeoff funnel" and so does at least not violate the departure clearance requirements. As explained in section IV, this not yet a proof of compliance but a pass indicator. Further investigation so lead us to

Phase 2: Examination of the obstacle identification surface (OIS) and PDG according to ICAO PANS-OPS Vol. II.

Results: This sub-step shows that the obstacle violates the OIS both laterally and vertically. As such, a PDG update is necessary providing a further pass indicator (see TABLE V):

TABLE V. COMPARISON OF MINIMUM PROCEDURE DESIGN GRADIENTS

Minimum PDG [%]	
as published[4]	required
6.30	5.90

Consequently, despite the identified OIS violation, the obstacle will not vertically impact the published takeoff procedure, the pass indicator is positive, leaving us with

Phase 3: Examination of the protection area for turns according to ICAO PANS-OPS.

Results: We derive that the obstacle is located inside the protection area of BIBTI 3E. However a calculation of the maximum allowable object height at the given location shows remaining clearance so that this pass indicator is also set true.

In total, we find all three pass indicators on true without granting combined lateral & vertical compliance so that we will have to continue with step 3:

4) DOM Step 3: Lateral Performance Analysis

By additionally considering the uncertainties resulting from adverse conditions and engine failure for all relevant aircraft types (e.g. A321, A340, B777F) in the TLPM, Figure 17 depicts the exemplary results of the missed approach performance analysis (OEI right prior passing the obstacle):

[3] This is the turning departure route BIBTIE 3E.

[4] restricted by other obstacles resp. environmental constraints.

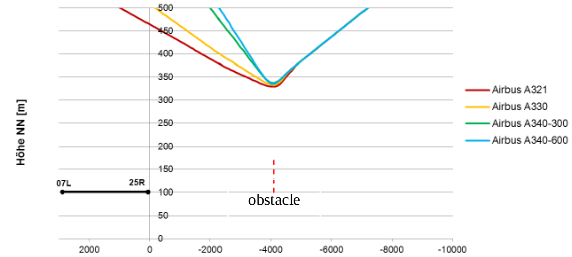


Figure 17. Missed App degraded performance analysis (scenario 2 &3)

Results: The calculations proved that yaw motion induced by engine failure and crosswind (up to 20 kt) can be fully compensated by aircraft flight control. Consequently no relevant neither lateral nor vertical deviations from the intended trajectory were identified for scenario 1 to 3 (partly shown in Figure 17). Scenario 4 however showed vertical violations requiring the execution of step 4.

5) DOM Step 4: Lateral Flyability of the critical trajectory

All aircraft types able to complete the turning departure as set out with the critical trajectory are being identified. So we calcite the required climb out speed v_2 to reach the pre-set turn radius r linked as follows

$$v = \sqrt{r \cdot g \cdot \tan(\Phi)} \geq v_2 \qquad (4)$$

delivering the following figures:

TABLE VI. REQUIRED OPERATIONAL PARAMETER CONFIGURATION FOR THE CRITICAL TRAJECTORY

Value	Unit	Numerical Value
Design Speed (v)	[m/s]	≈ 54 (105 kt)
Turn Radius (r)	[m]	1.100
Maximum Bank Angle (Φ)[5]	[°]	15
Takeoff Safety Speed v_2	[m/s]	≤ 54 (105 kt)

Comparison of design speed (v) with v_2 for all relevant aircraft models revealed that the required speed can only be achieved by small multi-engine jet or turboprop aircraft (e.g. Cessna C525A CJ2 or Beechcraft King Air B200GT). Even though this aircraft category is rather rare at FRA (close to pass indicator), we will have to identify the remaining risk being assessed in the final Step 5.

6) DOM Step 5: Vertical Performance Analysis of the critical trajectory

We finally determine CG and lift-off points under the prescribed unfavorable OEI conditions to calculate the pass altitudes above the obstacle for this aircraft category, again using TLPM.

TABLE VII depicts the results for the exemplary members of this aircraft category.

[5] Pursuant to ICAO PANS-OPS (Pt. 1 - Section 2, Chapter 3, Table I-2-3-1) the maximum bank angle until 305 m (1,000 ft) altitude for departures is given by $\Phi = 15°$.

TABLE VII. VALUES FOR EXAMPLE CALCULATION OF CROSSING ALT.

Aircraft	Climb Gradient [%]	Lift-off Point [m]	Crossing Altitude [m]
B200GT	5.5	840	160.80
C525A	3.6	1550	52.24

As a result we could prove in step 5 that also the critical aircraft category can safely overfly the critical obstacle with significant clearance according to PANS OPS (e.g. 35ft / 10m). So the SA for this safety case closes with a positive result.

If however, even step 5 would fail (or any preceding step beforehand) the SA methodology allows the investigation to set out mitigation measures such as canceling a published route, setting stricter prerequisites to allow fling that route (increased PDG or turn radius requirements to aircraft) or just generating appropriate awareness through hot spot advisories in the Aeronautical Information Publications (AIP).

VI. CONCLUSIONS – INTEGRATION CONCEPT INTO ICAO DOC. 9774

Aeronautical studies are supportive means to assess the safety and regularity of operations around airports with ICAO non-compliant obstacles in place (e. g. one that violates the OLS). Doc 9774 however does not provide any guidance on how to perform such study.

This paper presents a methodology which may contribute to standardization: Dealing with both statistically representative hazard scenarios and seldom events systematically investigated through scenario techniques, the presented model generates a complete risk picture, which proved usefulness in several certification processes with the German Ministry of Transport and the German ANS Supervisory Authority BAF. The statistical part relies on dedicated ANP value calculations, stochastic functional approximation leading to validated, procedure-specific probability density functions along any flight track allowing calculating obstacle CR through double integration. For the rare cases (often called as "PDF tails") we developed a scenario configuration technique assuming worst case environment and aircraft performance related conditions. The resulting 3D trajectories generated through the author's takeoff and landing performance model (TLPM) allows a deterministic (yes/no) collision potential determination by calculating minimum horizontal and vertical performance under unfavorable conditions for all aircraft categories operating at the investigation airport.

As such, we feel strong potential to see the presented methodology as a potential candidate for an ICAO DOC 9774, Appendix 3 supplement to give specialist a guideline on how to judge adequacy of formally non-compliant obstacles with safe and regular operations at the airport. It also reveals the need for updating and extending current ICAO's collision risk model with correct, procedure and flight phase specific ANP values.

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