Heliyon 9 (2023) e18378

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Collision risk assessment between aircraft and obstacles in the areas surrounding airports

Laura Moretti [*], Raducu Dinu, Paola Di Mascio

Department of Civil, Constructional and Environmental Engineering, Sapienza University of Rome, Via Eudossiana 18, 00184, Rome, Italy

A R T I C L E I N F O

Keywords:
Obstacle limitation surface
Risk of collision
Obstacles
Risk assessment
Aviation safety
Accident prevention

A B S T R A C T

The topographical features of a site and the anthropogenic artefacts inside and outside the airport boundaries influence the infrastructure use. Objects penetrating the obstacle limitation surfaces (OLS) or standing outside those surfaces have to be mapped and risk-assessed because they could be a hazard to air navigation. This study aims to quantify the risk of collision between aircraft and obstacles in the airspace. There are no available procedures in the literature: the authors supposed that the obstacle type and the examined OLS affect the collision risk. The proposed risk values and amplification factors derive from interviews with technicians. The methodology has been implemented in an existing airport with 589 penetrating obstacles: the results highlight that 69.8% of obstacles imply a negligible risk, and 3.7% require further analyses by the competent aviation authority. In this study, buildings and pylons penetrating the Transitional Surface are the most hazardous obstacles.

1. Introduction

In the last two decades, the air transport market liberalisation impacted the sector whose carriers, routes, and stopovers have multiplied [1,2]. In the pre-COVID-19 period, the International Air Transport Association (IATA) expected that passengers increase from 3.8 billion in 2017 to around 7.2 billion in 2035 [3]. Although this near doubling of today's level has different growth rates worldwide [3], this trend in passenger and freight traffic will determine the need to develop aeronautical and non-aeronautical management activities [4–6]. The challenge will not be played only on the quantitative adjustment [7]: it will be necessary to study future airport strategies [8,9] and to pursue international civil aviation policies to ensure a safe, efficient, economically sustainable, and environmentally responsible civil aviation sector [10–14]. Several studies in the literature focused on aviation safety modelling and assessing accident risk at airports. In particular, different areas of the airport airside have been analysed to identify the best strategies [15–18]. Indeed, the construction and adaptation of the airport infrastructures and facilities should comply with the criteria of the airspace configuration [19–21]. ICAO [22] and the European Regulation [23–25] on aeronautical safety and airport construction and management define a set of imaginary surfaces that should not be perforated by obstacles. Only some frangible objects (such as visual and-navigational aids required to be there by function) and existing immovable objects (including any other object shielded by that immovable one) can penetrate obstacle surfaces. The obstacle limitation surfaces (OLS) are intended to protect aircraft in flight and consist of the following (Fig. 1):

* Corresponding author.
E-mail address: laura.moretti@uniroma1.it (L. Moretti).

https://doi.org/10.1016/j.heliyon.2023.e18378
Received 3 November 2022; Received in revised form 16 May 2023; Accepted 15 July 2023
Available online 17 July 2023

- Outer Horizontal Surface (OHS)
- Conical Surface (CS)
- Inner Horizontal Surface (IHS)
- Approach Surface (AS)
- Take-off Climb Surface (TOCS)
- Inner Approach Surface (IAS)
- Transitional Surface (TS)
- Inner Transitional Surface (ITS)
- Balked Landing Surface (BLS)

OLSs provide volumes of airspace around and above the airport runway(s) to ensure safety for an aircraft in a flight operation [26]. In such areas, possible infringements of OLSs would cause interference with regular operations (i.e., as safe landing, take-off, or circling manoeuvres). According to ICAO Annex 14 [22], the dimensions and slopes of OLS depend on the airport reference code and the operational use of the runway. The same characteristics are required by specifications related to the obstacle clearance limits in the EASA Certification Specifications (CS) and Guidance Material (GM) for Aerodromes Design (ED Decision 2014/013/R) [25]. All surfaces should be kept free from fixed (temporary or permanent) and mobile objects or parts thereof, but these surfaces are often penetrated [27]. In this case, Procedures for Air Navigation Services - Aircraft Operations (PANS-OPS) have to be studied to develop instrument flight procedures and, when necessary, specify minimum safe altitudes/heights for each procedure segment [28]. The flight procedure can be studied according to the Collision Risk Model [29] to demonstrate an equivalent safety level despite the violation of the standards. The procedure and/or minimum heights may vary with the typical operational speeds of each aircraft, the navigational aid used both on the ground and onboard the aircraft (ILS) or onboard of aircraft only (WAAS). In the literature, recent research [30, 31] examined flight route radar data to assess the likelihood of aircraft deviating from their ideal routes. Indeed, aircraft safety during airborne operations depends on the obstacle clearance surfaces [27]. The aircraft deviation estimated through the location tracking platform Navtrack [32] made possible the calculation of safe and efficient OLS dimensions and the assessment of the risk level due to the obstruction penetration [33]. According to Ref. [30], the OLSs represent surfaces beyond which the probability of collision with an obstacle is below an acceptable safety level. The quantitative results show a noticeable difference between the existing OLSs and their estimated size based on the observed flight paths. In particular, the estimated lateral dimensions of the approach surfaces were lower than those defined by Ref. [22], especially for visual meteorological conditions (VMC) approaches which often require more vertical space than instrument meteorological conditions (IMC) approaches. According to some research, all take-off observed surfaces required more lateral dimensions and less vertical space than existing surfaces to provide an acceptable level of safety. On the other hand, some OLS may be overrated with respect to the path directions (i.e., lateral, vertical, and longitudinal) that affect the deviation probability [30].

The advent of modern technology improved navigation techniques, and the availability of more sophisticated tools permits to manage digital data of the terrain and obstacles. An electronic database relating to the orography and obstacles can support the air navigation in ground proximity warning system (GPWS) with terrain warning and representation system (TAWS) and minimum safety altitude warning system (MSAW) [34], the definition of contingency procedures to be used in the event of an emergency during a missed approach or take-off, analysis of aircraft operational limitations, design of instrumental procedures (including circling procedures), determination of the en-route drift-down curves and localisation of the en-route emergency landing sites, Advanced Ground Movement Guidance and Control System [35], production of aeronautical maps and onboard databases, flight simulator, and airport obstacles [36,37]. In particular, digital data are used by the Enhanced-Ground Proximity Warning System (EGPWS) to inform the onboard crew about the potential impact of the ground and/or obstacles [38]. Indeed, EGPWS provides timely alerts to allow the pilot to take corrective action [39]. These data are also used to identify and display the minimum safety altitudes for flight operations (e.g.

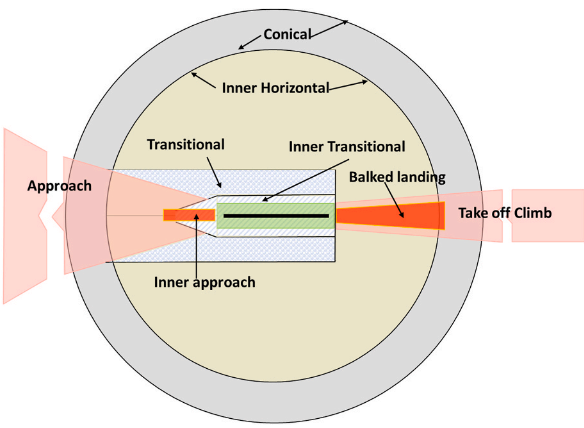

Fig. 1. OLS.

for digital pilot flight bag use) and increase awareness of the pilot by avoiding potential impact. However, obstacles that cannot be removed because they are orography or because they exist or are built for public interest need to prevent the aircraft from flying above the minimum free height of obstacles [40]. Therefore, the collision risk should be managed by preventive information to the pilot and route planning. Many studies in the literature present the application of Collision Risk Models (CRM) to assess the level of safety in European airports. These are based on in-depth analysis of radar data [41,42] and apply the criteria included in ICAO [29] and FAA [43] manuals. CRM is used to estimate the probability of collision between an approaching aircraft and existing obstacles.

This study aims to create an automatic mathematical model to calculate the coordinates of the current OLS of any airport, considering its runway characteristics and operations, and automatically draw the OLS and locate the obstacles. This model allows the identification in a CAD environment of the obstacles that penetrate the OLS of the examined airport. The identified critical objects are focused on by an innovative proposed methodology to assess the risks from penetrated surfaces. An aeronautical risk level is proposed for each airport obstacle considering its type, latitude, longitude, height of the ground, and elevation from the ground. Airspace experts, pilots, and airport managers provided primary data to carry out the study implemented in an Italian airport. The model allows the authority to decide if an obstacle penetrating OLSs could be maintained. The procedure can be the first step for the in-depth study of the specialists who define the airport operational procedures and aeronautical evaluations of the obstacles.

2. Materials and methods

Geoprocessing with Geographic Information System (GIS) and databases is widely used for automatic or semi-automatic mapping. This process contributes to a dynamic and integrated origination, processing, and provision of aeronautical information through the supply and exchange of digital aeronautical digital data [44]. The ICAO electronic aeronautical terrain and obstacle maps are available for all airports regularly used by international civil aviation according to the International Organization for Standardization (ISO) 19, 100 series of geographic information standards [45]. This electronic card supports the limitation and removal of airport obstacles, moving from the traditional Aeronautical Information Service to the Aeronautical Information Management (AIM). AIM provides a framework for dynamic and integrated management of digital aeronautical geographic information. According to ICAO Annex 15 [46],

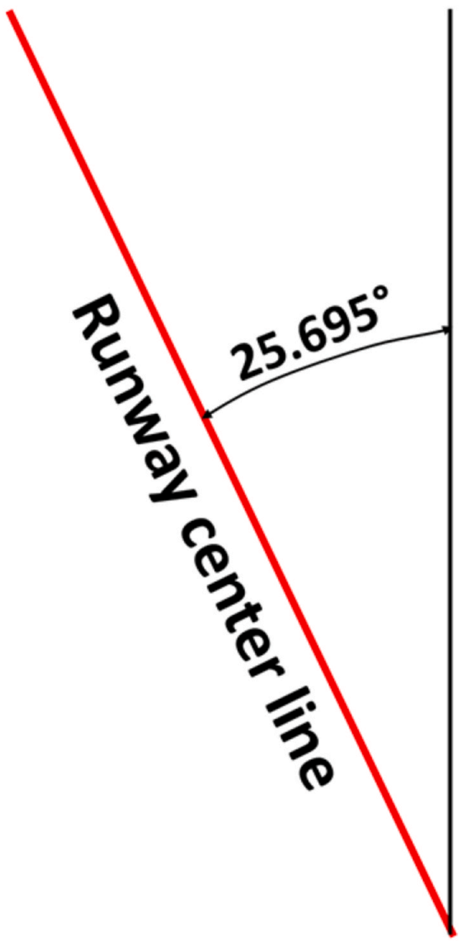

Fig. 2. Runway alignment.

obstacles are all fixed (whether temporary or permanent) and mobile objects, or parts thereof, that:

- are located on an area intended for the surface movement of aircraft or extend above a defined surface to protect aircraft in flight. They penetrate OLSs or their height above ground level is over than a minimal value [46]. Broadcast transmission antennas, cell phone masts, electricity transmission pylons, wind turbine farms, chimneys, elevated tanks, cableway and cableway stations, pylons for radio links, overhead electricity conductors (power lines), cableway systems, cableways, chairlifts, and any artefact whose vertical development could constitute a danger for air navigation are considered as vertical obstacles;
- stand outside those defined surfaces and have been assessed as a hazard to air navigation. According to Ref. [47], adequate space must be provided between an aircraft and the ground or obstacles through properly designed flight procedures.

Therefore, in addition to the constraints deriving from OLS boundaries, it is necessary to limit activities or construction in the areas surrounding an airport to reduce potentially dangerous situations for air navigation (for example, construction of fuel depots due to the danger of explosions and fires, or artificial lakes and ponds due to the bird strike hazard). The obstacles should be identified and lighted according to Ref. [22]. Airborne Laser Scanning (LiDAR) has been adopted to collect points because it ensures high measurement accuracy, degree of automation, and future development [48]. The used 3D Terrestrial Laser Scanner provided data acquisition with 5 mm accuracy/3 mm repeatability, a measurement range over 500 m, and a measurement rate of 122,000 points/sec. The instrument allowed a field of view of 100° vertical and 360° horizontal and had an integrated Global positioning receiver, an onboard inclination sensor, and an integrated compass for georeferencing and automatic alignment of scans. Moreover, the instrumentation was interfaced with a metric camera to acquire images suitable for covering the survey area and to generate high-definition orthophotos and textures. The obstacle and terrain data numerical requirements used to model the Digital terrain model and the digital surface model complied with [46] in terms of vertical accuracy, vertical resolution, horizontal accuracy, confidence level, integrity classification, and maintenance period.

OLS depend on the geometrical and functional characteristics of the runway: the length and strip, the distances declared in the Aeronautical Information Publication (i.e., Take-Off Run Available, Take-Off Distance Available, Stopway, and Clearway), the xyz coordinates of thresholds and the Airport Reference Point (ARP) are input data for the risk analysis. In this study, the automatisation of the drawing is based on geographical coordinates. Therefore, the angle (α) between the runway longitudinal axis (red alignment in Fig. 2) and the geographical reference (white alignment in Fig. 2) was defined, and it measures 25.695°.

Given the runway alignment and functional characteristics, an automatic procedure in the Visual Basic (VBA) environment identifies the OLS geometrical criteria in terms of length, slope, distance, and divergence. Table 1 refers to a 4E instrumental precision approach runway.

The OLS coordinates are then identified. Equations (1)–(18) present the analytical procedure to identification of the vertices P_i=(x_i, y_i, z_i (i = 1, …, 6) of TOCS (Figs. 3–5):

Table 1
OLS characteristics.

OLS	Dimension		Value	Unit
AS	Length inner side		300	m
	Distance from the threshold		60	m
	Divergence		15	%
	First section	Length	3000	m
		Slope	2.0	%
	Second section	Length	3600	m
		Slope	2.5	%
	Horizontal section	Length	8400	m
CS	Slope		5.0	%
	Height		100	m
IHS	Height		45	m
	Radius		4000	m
TOCS	Length of the inner edge		180	m
	Final width		1800	m
	Distance of inner edge from TORA end		60	m
	Rate of divergence (each side)		12.5	%
	Overall length		15,000	m
	Slope		2.0	%
OHS	Radius		15,000	m
TS	Slope		14.3	%
ITS	Slope		33.3	%
IAS	Width		120	m
	Distance from the threshold		60	m
	Length		900	m
	Slope		2.0	%
BLS	Inner side length		300	m
	Distance from the threshold		1800	m
	Rate of divergence (each side)		10	%
	Slope		3.33	%

$$X_1 = X + (CWY \times \sin \alpha) + (L_i / 2 \times \cos \alpha) \tag{1}$$

$$Y_1 = Y + (CWY \times \cos \alpha) + (L_i / 2 \times \sin \alpha) \tag{2}$$

$$Z_1 = Z \tag{3}$$

$$X_2 = X_1 + ((L_f / 2 - L_i / 2) / Div.) \times \sin \alpha + (L_f / 2 - L_i / 2) \times \cos \alpha \tag{4}$$

$$Y_2 = Y_1 - ((L_f / 2 - L_i / 2) / Div.) \times \cos \alpha + (L_f / 2 - L_i / 2) \times \sin \alpha \tag{5}$$

$$Z_2 = Z_1 + ((L_f / 2 - L_i / 2) / Div.) \times P \tag{6}$$

$$X_3 = X_2 + (L - (L_f / 2 - L_i / 2) / Div.) \times \sin \alpha \tag{7}$$

$$Y_3 = Y_2 - (L - (L_f / 2 - L_i / 2) / Div.) \times \cos \alpha \tag{8}$$

$$Z_3 = Z_2 + (L - (L_f / 2 - L_i / 2) / Div.) \times P \tag{9}$$

$$X_4 = X_3 - (L_f \times \cos \alpha) \tag{10}$$

$$Y_4 = Y_3 - (L_f \times \sin \alpha) \tag{11}$$

$$Z_4 = Z_3 \tag{12}$$

$$X_5 = X_4 - (L - (L_f / 2 - L_i / 2) / Div.) \times \sin \alpha \tag{13}$$

$$Y_5 = Y_4 + (L - (L_f / 2 - L_i / 2) / Div.) \times \cos \alpha \tag{14}$$

$$Z_5 = Z_2 \tag{15}$$

$$X_6 = X_1 - L_i \times \cos \alpha \tag{16}$$

$$Y_6 = Y_1 - L_i \times \sin \alpha \tag{17}$$

$$Z_6 = Z_1 \tag{18}$$

where L is the total length, L_i is the initial width, L_f is the final width, P is the slope, and Div. is the divergence.

For the sake of brevity, the Equations to identify other coordinates of all OLSs are not described. At the end of the process, the VBA coordinates are exported to the CAD environment. The obtained digital 3D model of the scenario allows the identification of the obstacles collected in the Digital Terrain Model (DTM) that penetrate OLS. Given a position on the ground near the airport (i.e., X,Y coordinates), the comparison between the elevation of the obstacles (Z), the ground (Z_{ground}), and the OLS (Z_{OLS}) gives the relative penetration and the obstacle prominence according to Equation (19) and Equation (20), respectively.

$$\text{Relative penetration} = Z/Z_{OLS} \tag{19}$$

$$\text{Obstacle prominence} = Z/Z_{ground} \tag{20}$$

This study aims to provide a quantitative procedure to assess the aeronautical risk from obstacles penetrating or not the OLS and

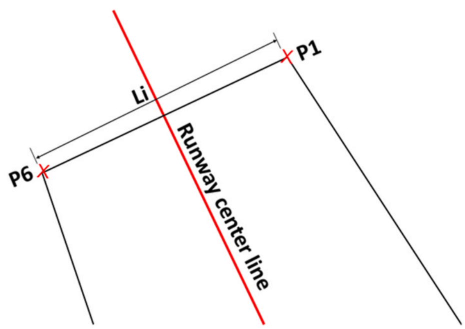

Fig. 3. P_1 and P_6 of TOCS.

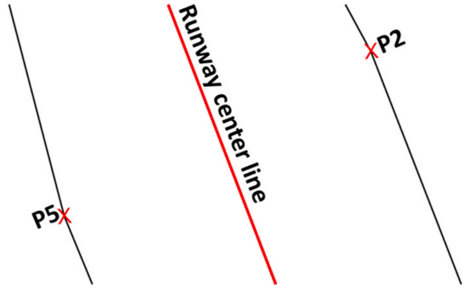

Fig. 4. P_2 and P_5 of TOCS.

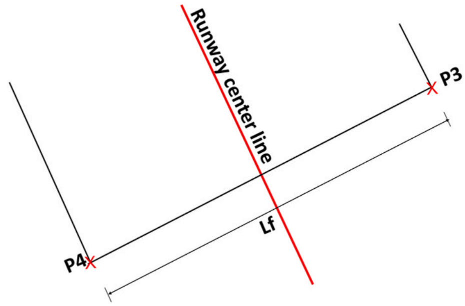

Fig. 5. P_3 and P_4 of TOCS.

support the authority to decide if an obstacle penetrating the OLSs could be maintained. The procedure can be the first step for the in-depth study of the specialists who define the airport operational procedures and aeronautical evaluations of the obstacles. In this study, the collision risk with an obstacle depends on the obstacle type and the examined OLS. The methodology is consistent with probability and damage quantification methods published in the literature. The proposed risk values and amplification factors derive from interviews with a panel of technicians from different backgrounds, experts and professionals in the aviation sector, and airport and air traffic management (i.e., data listed in Tables 2 and 3, and the amplification factors). Thirty-six technicians, all with experience in airport planning and design, operations and definition of flight procedures, have participated in the interviews: 9 aeronautical engineers, 9 pilots, 9 air traffic controllers, and 9 airport managers. The geometric mean has been used to aggregate their judgments.

The risk level from the OLS penetration (l_s) depends on the affected surface. l_s ranges between 100 (if AS is penetrated) and 50 (if OHS is penetrated); l_s is 0 if the obstacle does not penetrate OLS, but it is considered a hazard for air navigation. IAS, ITS, and BLS are not listed in Table 3 because fixed objects are not permitted above these surfaces.

Moreover, amplification factors are proposed to consider the environmental conditions:

- f_q depends on the ratio between the elevation of the obstacle and the OLS elevation at the same x-y coordinates (Equation (19));
- f_g depends on the ratio between the elevation of the obstacle and the ground elevation at the same x-y coordinates (Equation (20));
- f_i depends on the distance (in m) from the nearest obstacle according to Equation (21):

$$f_i = \sqrt{d}/10 \tag{21}$$

- f_d depends on the distance of the obstacle from ARP according to Equation (22):

Table 2
Risk level for penetrated OLS.

penetrated OLS	l_s
AS	100
TOCS	90
TS	80
IHS	70
CS	60
OHS	50

Table 3
Risk level for obstacle type.

Obstacle type	l_o
Mains cable	100
Electricity pylon	90
Pole	80
Chimney	70
Crane	60
Tree	50
Lighting pole	40
Building	30
Ground	20

$$f_d = {}^{10}/_{D} \tag{22}$$

where D is the distance of the obstacle from ARP in m.

Equation (23) gives the risk value from the penetrated OLS (R_s):

$$R_s = l_s \bullet f_q \bullet f_g \bullet f_i \bullet f_d \tag{23}$$

Concerning the obstacle type and its hazard level and according to Ref. [49], the more visible it is, the less hazardous it is. In this study, the authors proposed the risk levels (l_o) in Table 3: it is a value between 0 (the lowest risk) and 100 (the maximum risk).

For obstacles not listed in Table 3, the risk level should be assigned based on their visibility.

Moreover, amplification factors are proposed to consider the environmental conditions:

- the factor depending on the traffic (f_t) is 0.1 for dominant Visual Flight Rules (VFR) operations and 0.02 for dominant Instrument Flight Rules (IFR) movements;
- the factor depending on the obstacle lighting (f_l) is 0.1 for lighted obstacles and 1 for non-lighted obstacles;
- the factor depending on the obstacle signalling (f_s) is 0.5 for non-signalled obstacles and 0.1 for those signalled according to ICAO (2018).

Equation (24) gives the risk value from the obstacle type (R_o):

$$R_o = l_o \bullet f_t \bullet f_l \bullet f_s \tag{24}$$

Finally, the risk for air navigation due to an obstacle near the airport(R) is assessed according to Equation (25):

$$R = R_o + R_s \tag{25}$$

If an obstacle penetrates more surfaces, the most hazardous condition is considered.

The proposed methodology has been implemented to assess the risk of collision for obstacles penetrating the OLS of an existing Italian airport. The 15/33 runway is 2200 m long and 45 m wide. It can be used in both directions for take-off and landing operations. Runway 15 is the preferential runway in both VFR and IFR conditions and is equipped for precision instrument landings with an ILS CAT 1 system. Precision instrumental approaches for runway 33 are not currently published.

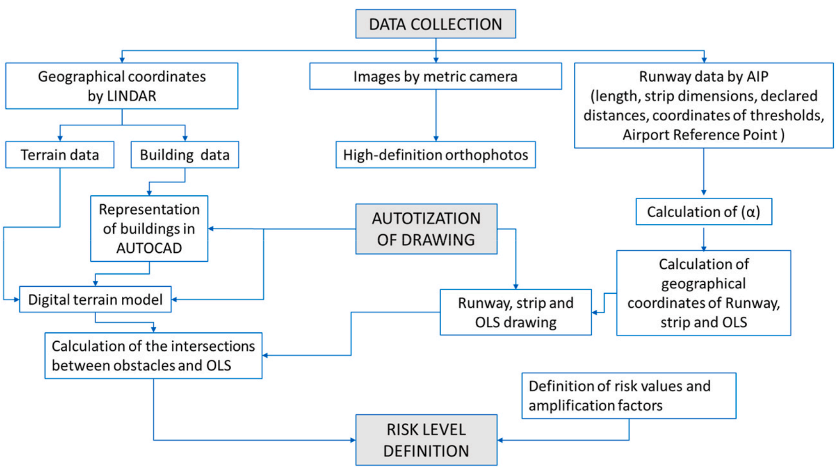

Fig. 6. Procedure flow chart.

Fig. 6 shows the flow chart of the whole procedure.

The results allow for an objective assessment of the collision risk level, and their values are comparable to a target level of risk to be defined during the analysis. In this study, the results from the risk analysis have been sorted in decreasing order to identify the most severe aeronautical risk to be managed priorly by the airport manager.

3. Results

The coordinates of the runway and OLS in VBA allowed drawing the CAD model to identify the obstacles to be considered (both penetrating and not). Fig. 7 shows the TOCS (the red area surrounded by a green line) and the runway (the green line).

The overall CAD model for the examined runway and its OLS is in Fig. 8.

In the VBA environment, the objects penetrating OLS and the hazardous objects near the airport are considered, and their coordinates are compared with the digital model to identify the most critical conditions. For this purpose, Table 4 shows the analysis of some points where an obstacle (whose coordinates are X, Y, Z) over the ground or the orography (Z_{ground}) causes the penetration of OLS (whose coordinates are X, Y, Z_{OLS}) (i.e., percentage penetration in Table 4 more than 1 according to Equation (19)). Moreover, data in Table 4 allow the identification of the most hazardous obstacles for each OLS (i.e., the highest value of obstacle prominence according to Equation (20)). All coordinates consider a local coordinate system for confidentiality reasons.

The obstacles penetrating OLS are then identified in the 2D CAD model. In Fig. 9, the blue points highlight the obstacles penetrating TOCS.

Moreover, by combining geometrical data from topographic DTM and functional parameters from airport operational procedures defining the OLS it is possible to obtain a 3D model (Fig. 9). Thus, it became useful managing complex environmental and functional frameworks where orography, anthropic activities, and airport operational procedures interact. Indeed, Fig. 10 gives efficient support to plan (or verify) approach and departure procedures with respect to the natural obstacles in the areas around the airport. For instance, in the area south of the airport, the natural terrain represents an obstacle that penetrates the surface AS33, which is aligned to the runway centreline to allow ILS approaches. On the other hand, the departure climb path from threshold 15 is curved due to the orography.

Then, the quantitative risk analysis should not ignore the geometrical detail of singular obstacles penetrating OLS that cannot be observed in the 3D representation. The automatic VBA procedure has identified 589 obstacles to be compiled and analysed. In the case study, 162 obstacles more than those listed in the current Aerodrome Obstacle Chart type A have been identified. Fig. 11 shows the statistical distribution of the assessed collision risk. It shows that the number of obstacles decreases when the risk increases.

The graphical results highlight that the distribution of the collision risk in the areas near the airport has an exponential trend. Most obstacles (i.e., 69.8% of the identified objects) have a negligible risk (R less than 199), while 3.7% have R over the threshold value of 400. Such threshold collision risk has been identified in the current study as the value of R requiring further analyses by the Italian Civil Aviation Authority. In this study, the most hazardous obstacles are buildings (l_o equal to 30) or electric pylons (l_o equal to 90) penetrating TS (l_s is 90), while these do not refer to the highest base factors. Instead, their geometric (height and position) and environmental (VFR operations and absence of lighting and signalling) characteristics make them the most critical around the examined airport. Table 5 lists the details of the obstacles whose R is higher than 400.

Given the impossibility removing such obstacles or reducing their height under their relevant Z_{OLS}, proper obstacle management requires, at least, signalling and lighting them according to Ref. [22].

4. Discussion

Reliable models quantifying the collision risk should address the precise position, shape, and temporality of obstacles near the airport by providing additional information (e.g., lighting and signalling). A proper model should adapt its structure to the conditions to be described. A multi-level approach is necessary when the obstacles are complex or are evolving. In this case, a too simple model has a negative effect because it could recommend flight operations in an area larger than needed. Moreover, a model should be dynamic to reflect both permanent and variable characteristics of the environment: while the orography and some constructions (pylons, chimneys, etc.) are static, some other obstacles can be dynamic to different degrees (e.g., tower cranes, mobile cranes, concrete pump

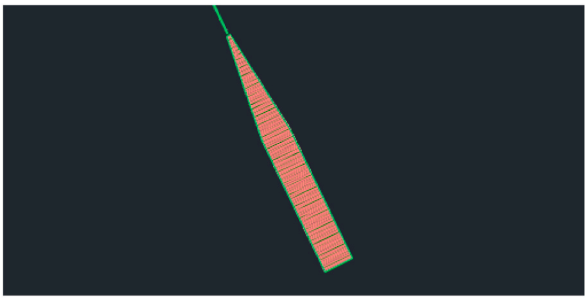

Fig. 7. Runway and TOCS.

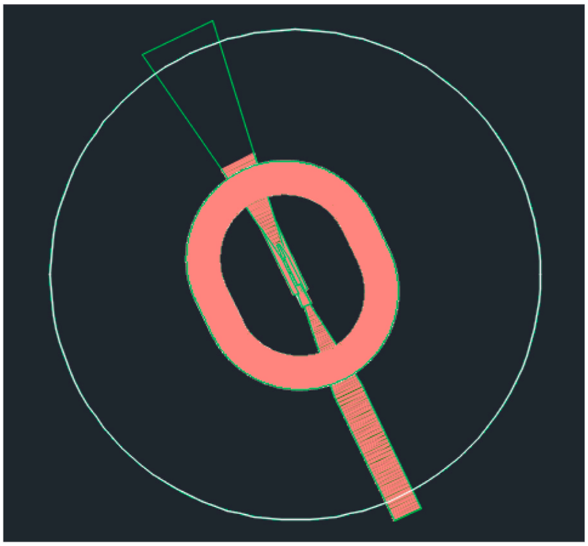

Fig. 8. Overall runway and OLS model.

Table 4
Identification of the most hazardous obstacles.

ID obstacle	X (m)	Y (m)	Z (m)	Zground (m)	OLS	ZOLS (m)	percentage penetration (%)	obstacle prominence (%)
OBS_015	19748.2	31581.5	113.0	101.0	AS	138.7	105	112
OBS_287	23612.8	24851.6	310.0	301.6	TOCS	234.6	103	132
OBS_274	22791.8	26073.3	232.4	219.9	IHS	175.2	106	133
OBS_578	20299.6	30562.0	141.5	116.4	TS	124.1	114	122
OBS_522	25146.7	29785.4	299.72	273.79	CS	200.38	150	109
OBS_195	23738.1	24252.4	320.37	308.55	OHS	249.06	129	104

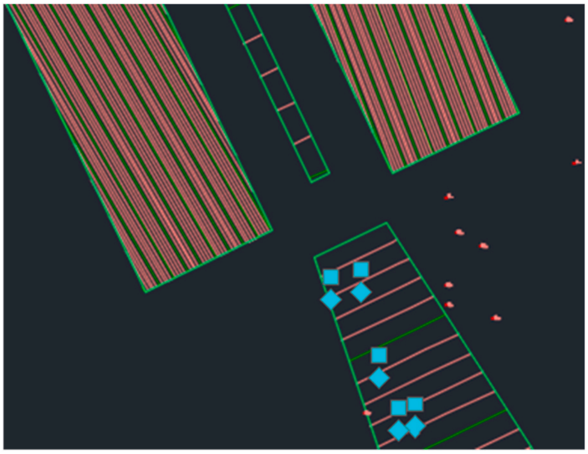

Fig. 9. Obstacles penetrating TOCS.

trucks, other construction equipment, etc.). The temporality in the model helps to update the state and the associated risk of an obstacle considering its planned phase, construction, existing, planned for removal, being removed, and removal status.

Therefore, a 3D representation permits the integration of digital models (DTM, obstacles, etc.) and quantitative risk analysis and overcomes the critical issues of the traditional approach due to the operational burden and the disaggregated perspective of the aspects concerning possible interference. The singular verification associated with the traditional method provides a binary outcome valid for each obstacle under a specific procedure. On the other hand, the proposed 3D modelling allows immediate and complete identification of interferences through direct observation of the model, providing the operator with both an overview of the system and the possibility of exploring the space, thus helping the more efficient flight procedure identification.

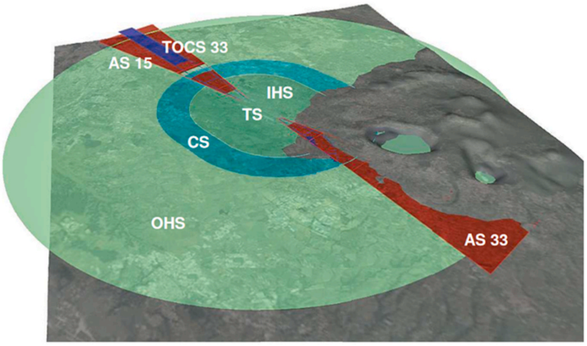

Fig. 10. 3D model.

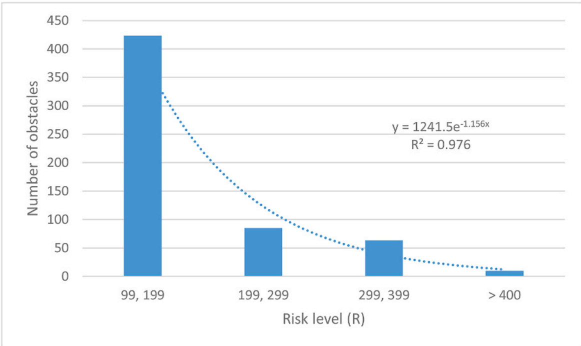

Fig. 11. Statistical distribution of the assessed collision risk values.

Table 5
Details of the most hazardous obstacles.

ID obstacle	X (m)	Y (m)	Z (m)	Zground (m)	OLS	ZOLS (m)	Obstacle type	R
OBS_563	20395.2	30357.2	141.8	119.6	TS	138.7	building	1726
OBS_565	20440.9	30261.2	132.8	121.0	TS	234.6	building	868
OBS_578	20299.6	30562.0	141.5	116.4	TS	175.2	building	695
OBS_564	20477.9	30329.1	144.8	119.6	TS	124.1	building	558
OBS_569	20576.2	30129.8	141.1	122.8	TS	200.3	building	494
OBS_577	20361.5	30508.8	142.8	118.0	TS	249.0	building	483
OBS_547	19865.4	31440.8	114.0	105.7	TS	249.0	electricity pylon	447
OBS_562	20454.6	30547.5	145.1	118.9	TS	249.0	building	417
OBS_567	20510.3	30160.7	142.9	122.8	TS	249.0	building	402

The proposed methodology allows an integrated approach that summarises topographical and functional data to be interpreted with a quantitative model defined based on information from airport and aviation experts. The input parameters describe a complex environment with the minimum data to consider, with a reliable risk assessment. The results permit to determine the maximum permissible height of an obstacle. If necessary, it returns an acceptable risk based on the most dangerous obstacles to ensure and maintain a high level of safety. In this study, the threshold value of R to be managed is 400 because it identifies the most critical conditions. However, other studies should be carried out to identify a unified threshold value valid for all airports.

The combined terrain plus obstacles data processed in the 3D CAD model can also be used in other applications (e.g., flight simulator) to design new approach procedures. However, the model overlooks obstacles on top of other ones: an antenna on the roof is modelled as a substantially square-shaped building whose height is equal to the maximum height of the antenna. Moreover, further interviews with pilots and air traffic controllers shall be carried out to improve the model setting and increase its capability in describing anthropised areas.

5. Conclusions

Until the advent of the COVID-19 pandemic, air transport was expected to grow in the coming years, and the airports would have to expand their facilities to increase their operational capacity. Aeronautical authorities must maintain safe and efficient aeronautical operations inside and outside airports to reap the economic benefits deriving from the growing demand for air transport. The obstacle limitation surfaces protect aircraft against objects dangerous to operations near the airport. However, it may be impractical or impossible to meet the OLS requirements due to the limited space around airports. As a result, airports assess the risk of collision due to the boundary conditions and the modified surfaces.

The main objective of this study was to create an innovative methodology to assess the danger of each obstacle near a generic airport, to support the authority to decide if maintain or not the obstacle penetrating the OLSs. The proposed methodology consists of a topographic model and an innovative quantitative risk model. The first one is composed of an automatic procedure in VBA that overlaps the topographic data with the OLS to identify the critical conditions (i.e., penetrating obstacles or hazardous objects near the airport). The digital terrain and objects model from Airborne Laser Scanning allows for identifying the most critical OLS requiring risk assessment and whether modification of the flight procedures. The second part of the proposed methodology starts from the results of the geometric analysis considering base and amplification factors to assess the risk of collision. The former considers the obstacle types and penetrated OLSs, and the latter the environmental conditions. According to the answers of interviewed technicians from different backgrounds, main aerial power lines penetrating AS are the most severe base factors. In the examined case study 589 obstacles have been identified, 162 more than those listed in the Obstacle Aerodrome Chart of the examined airport. The most hazardous ones are buildings and a power line pylon penetrating TS in VFR operations, without lighting and signalling. Their R values represent the 97th percentile of the population of maxima and require deep analyses to identify the best strategies to ensure safe movements.

The presented methodology is a proposal based on geometric and environmental parameters. The proposed metric depends on unbiased base factors and amplification factors defined by the authors according to the international standards for aviation and the experience of airspace experts, pilots, and airport managers. The results allow a quantitative approach to manage risk and assess the effectiveness of possible countermeasures. So far, the topographic survey of only one airport has been completed, and the surveys of other airports are underway. The model will be further validated on these new surveys, and the number of interviews with the experts who defined the risk levels will be increased.

Author contribution statement

Laura Moretti, Raducu Dinu, Paola Di Mascio: Conceived and designed the experiments; Performed the experiments; Analysed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

The authors do not have permission to share data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The Authors thank Eng. Festim Hallulli and acknowledge his work. Mr Hallulli cooperated in the development of the earlier version of the risk model.

References

[1] M. Abate, P. Christidis, The impact of air transport market liberalization: evidence from EU's external aviation policy, Economics of Transportation 22 (2020), 100164, https://doi.org/10.1016/j.ecotra.2020.100164.
[2] G. Burghouwt, J.G. de Wit, The wake of liberalisation: long-term developments in the EU air transport market, Transport Pol. 43 (2015) 104–113.
[3] M. Arblaster, Economic Characteristics of Air Traffic Management, Elsevier Science, Amsterdam, the Netherlands, 2018, pp. 119–141, https://doi.org/10.1016/B978-0-12-811118-5.00006-0.
[4] P. Brooker, Future air traffic management: strategy and control philosophy, Aeronaut. J. 107 (2003) 589–598, https://doi.org/10.1017/S0001924000013804.
[5] M.J. Lee, C. Kim, A network DEA aeronautical and non-aeronautical production model: an application to South Korea airports, J. Econ. Struct. 7 (2018) 32, https://doi.org/10.1186/s40008-018-0130-2.
[6] M. Yousefzadeh Aghdam, S.R. Kamel Tabbakh, S.J. Mahdavi Chabok, M. Kheyrabadi, Optimization of air traffic management efficiency based on deep learning enriched by the long short-term memory (LSTM) and extreme learning machine (ELM), Journal of Big Data 8 (2021) 54, https://doi.org/10.1186/s40537-021-00438-6.
[7] M. de Gramatica, F. Massacci, W. Shim, U. Turhan, J. Williams, Agency problems and airport security: quantitative and qualitative evidence on the impact of security training, Risk Anal. 37 (2017) 372–395, https://doi.org/10.1111/risa.12607.
[8] B. Badanik, I. Laplace, N. Lenoir, E. Malavolti, A. Tomova, A. Kazda, Future strategies for airports, 27th Congress of the International Council of the Aeronautical Sciences 2010, ICAS 2010 6 (2010) 4416–4425.
[9] I. Laplace, A. Kazda, A. Tomova, B. Badanik, N. Lenoir, E. Malavolti, FAST: Future airport strategies, 8th Innovative Research Workshop and Exhibition, Proceedings, 2009, pp. 19–28.
[10] D.K. Yadav, H. Nikraz, Implications of evolving civil aviation safety regulations on the safety outcomes of air transport industry and airports, Aviation 18 (2014) 94–103, https://doi.org/10.3846/16487788.2014.926641.
[11] P. Di Mascio, D. Cervelli, A. Comoda Correra, L. Frasacco, E. Luciano, L. Moretti, S. Nichele, A critical comparison of airport capacity studies, J. Airpt. Manag. 21 (2020) 307–321.
[12] J.E. Green, Civil aviation and the environmental challenge, Aeronaut. J. 107 (2003) 281–300, https://doi.org/10.1017/S0001924000013579.

[13] P. Di Mascio, M.V. Corazza, N.R. Rosa, L. Moretti, Optimization of aircraft taxiing strategies to reduce the impacts of landing and take-off cycle at airports, Sustainability 14 (2022) 9692, https://doi.org/10.3390/su14159692.
[14] M.V. Corazza, P. Di Mascio, G. Esposito, Airports as sensitive areas to mitigate air pollution: evidence from a case study in rome, Environments 9 (2022) 108, https://doi.org/10.3390/environments9090108.
[15] Y. Yousefi, N. Karballaeezadeh, D. Moazami, A. Sanaei Zahed, S.D. Mohammadzadeh, A. Mosavi, Improving aviation safety through modeling accident risk assessment of runway, Int. J. Environ. Res. Publ. Health 17 (2020) 6085, https://doi.org/10.3390/ijerph17176085.
[16] S. Galagedera, V. Adikariwattage, H.R. Pasindu, Evaluation of rapid exit locations based on veer-off risk for landing aircraft, Sustainability 13 (2021) 5134, https://doi.org/10.3390/su13095134.
[17] L. Moretti, P. Di Mascio, S. Nichele, O. Cokorilo, Runway veer-off accidents: quantitative risk assessment and risk reduction measures, Saf. Sci. 104 (2018) 157–163. Scopus id=2-s2.0-85041471769.
[18] R.E. Caves, I. Kirkland, Runway overrun risk assessment, Transport. Res. Rec. 1662 (1) (1999) 67–73, https://doi.org/10.3141/1662-08.
[19] C. Barnhart, D. Fearing, A. Odoni, V. Vaze, Demand and capacity management in air transportation, EURO J Transp Logist 1 (2012) 135–155, https://doi.org/10.1007/s13676-012-0006-9.
[20] P. Di Mascio, L. Moretti, M. Piacitelli, Airport landside sustainable capacity and level of Service of terminal functional subsystems, Sustainability 12 (2020) 8784, https://doi.org/10.3390/su12218784.
[21] G. Solvoll, T.A. Mathisen, M. Welde, Forecasting air traffic demand for major infrastructure changes, Res. Transport. Econ. 82 (2020), 100873, https://doi.org/10.1016/j.retrec.2020.100873.
[22] ICAO Annex 14, Aerodromes - volume I - aerodromes design and operations, in: International Civil Aviation Organization, Canada, Montreal, Quebec, 2022.
[23] Commission Regulation (EU)No 139/2014 of 12 February 2014 Laying Down Requirements and Administrative Procedures Related to Aerodromes Pursuant to Regulation (EC) No 216/2008 of the European Parliament and of the Council (EASA ADR).
[24] Regulation (EC) No 1108/2009 of the European Parliament and of the council of 21 october 2009 amending regulation (EC) No 216/2008 in the field of aerodromes,air traffic management and air navigation services and repealing Directive 2006/23/ECEASA CS-ADR-DSN.
[25] Certification Specifications (CS) and Guidance Material (GM) for Aerodromes Design, Annex to DECISION 2014/013/R of the EXECUTIVE DIRECTOR of the AGENCY of 27 February 2014.
[26] D. Kim, W.Y. Kim, A case study on application of obstacle limitation criteria for specific conditions of airports, Journal of the Korean Society for Aviation and Aeronautics 24 (2016) 25–30, https://doi.org/10.12985/ksaa.2016.24.2.025.
[27] S. Litsheim, X. Xiao, Airport obstacle surfaces, J. Adv. Transport. 43 (2009) 347–366, https://doi.org/10.1002/atr.5670430306.
[28] Icao Doc 9137-AN/898 Part 6, Airport Services Manual Part 6 Control of obstacles (1983).
[29] ICAO, Manual on the Use of the Collision Risk Model (CRM) for ILS Operations, ICAO, Montreal, 1980. Doc 9274-AN/904.
[30] Sandaradura, A.S. Quantitative Risk Analysis of Obstacle Limitation Standards. (Doctoral Thesis). University of Calgary, Calgary, AB.doi:10.11575/PRISM/27508.
[31] A. Silva, A.G. de Barros, Quantitative risk evaluation of obstacle limitation surfaces for final approaches at airports, Journal of Aviation Technology and Engineering 5 (2) (2016) 5, https://doi.org/10.7771/2159-6670.1110.
[32] Navtrack. https://navtrack.com/, 2022. (Accessed 18 August 2022).
[33] X. Chen, R. Ji, T. Jiang, R. Zhao, A new flight procedure and obstacle limitation surface based approach to airport clearance area analysis, in: 2020 IEEE 2nd International Conference on Civil Aviation Safety and Information Technology, ICCASIT, 2020, pp. 864–868, https://doi.org/10.1109/ICCASIT50869.2020.9368796.
[34] D. Franjković, T. Bucak, N. Hoti, Ground proximity warning system- GPWS, Promet - Traffic & Transp. 11 (1999) 293–301.
[35] T. Ding, Analysis and simulation of advanced ground motion guidance and control system, in: IEEE 2nd International Conference on Power, Electronics and Computer Applications (ICPECA), 2022, 2022, pp. 383–386, https://doi.org/10.1109/ICPECA53709.2022.9718831.
[36] C. Lounis, V. Peysakhovich, M. Causse, Visual scanning strategies in the cockpit are modulated by pilots' expertise: a flight simulator study, PLoS One 16 (2021), e0247061, https://doi.org/10.1371/journal.pone.0247061.
[37] E. Pierrat, L. Rupcic, M.Z. Hauschild, A. Laurent, Global environmental mapping of the aeronautics manufacturing sector, J. Clean. Prod. 297 (2021), 126603, https://doi.org/10.1016/j.jclepro.2021.126603.
[38] B.C. Breen, Controlled flight into terrain and the enhanced ground proximity warning system, IEEE Aerosp. Electron. Syst. Mag. 14 (1999) 19–24, https://doi.org/10.1109/62.738350.
[39] M. Shidong, H. Yuncheng, W. Zhong, Y. Guoqing, Researches on simulation and validation of airborne enhanced ground proximity warning system, International Journal of Aerospace and Mechanical Engineering 6 (2012) 968–972.
[40] C. Wang, Y. Hu, V. Tao, Identification and risk modeling of airfield obstructions for aviation safety management, July, in: ISPRS20thInternational Society for Photogrammetry and Remote Sensing Congress, Istanbul, Turkey, 2004, pp. 12–23.
[41] Nieto Saez,F.J.;Arnaldo Valdes, R.; Gonzales Garciaa,E.J., Mc Auley,G.; Izquierdo,M.I. Development of a three dimensional collision risk model toolto assess safety in high density en route airspaces, 2010, Proc. ImechE Vol.224 Part g: J. Aero. Eng. DOI:10.1243/09544100JAERO704.
[42] Hartmut Fricke, Christoph Thiel, A methodology to assess the safety of aircraft operations when aerodrome obstacle standards cannot Be met* open, J. Appl. Sci. 5 (2015) 62–81.
[43] FAA-H-8083-2A risk management handbook, FAA (2022).
[44] G.P. Falavigna, A.L. Iescheck, S.F. de Souza, 3D modelling to identify and quantify obstacles in aerodrome protection zone, Bol. Ciências Geodésicas 26 (2) (2020), e2020009, https://doi.org/10.1590/s1982-21702020000200009.
[45] ISO, 2001. ISO/TR 19120, Geographic Information — Functional Standards, 2001, 19120, https://www.iso.org/obp/ui/#iso:std:iso:tr. accessed 8.18.22.
[46] ICAO Annex 15. Aeronautical information Services, in: International Civil Aviation Organization, Canada, Montreal, Quebec, 2018.
[47] ICAO Doc, 8168. Procedures for Air Navigation Services (PANS) - Aircraft Operations - Volume I Flight Procedures, Canada, International Civil Aviation Organization, Montreal, Quebec, 2006.
[48] Eurocontrol, Terrain and Obstacle Data (TOD) Manual, 2021. https://www.eurocontrol.int/publication/eurocontrol-terrain-and-obstacle-data-manual. accessed 6.18.22.
[49] ENAC Ente Nazionale per l'aviazione Civile (Italian Civil Aviation Authority), Regolamento per la Costruzione e L'esercizio Degli Aeroporti, second ed., Italian Civil Aviation Authority, Rome, Italy, 2014.