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ARTICLE

Operational issues and assessment of risk for light UAVs

G. Guglieri, F. Quagliotti, and G. Ristorto

Abstract: ENAC, the Italian Civil Aviation Authority, has published the regulation for remotely piloted aircraft systems (RPAS) with a maximum take-off mass of less than 150 kg. The aim of this paper is the application of Italian regulatory prescriptions for risk assessment to a family of RPAS. The results of this analysis, performed in collaboration with ENAC, are compared with other available methods, providing a comprehensive insight for mission feasibility and operational implications in a set of realistic application cases. Practical solutions are proposed for risk mitigation of RPAS specialized operations.

Key words: remotely piloted aircraft systems, unmanned aerial vehicles, certification procedures, risk assessment.

Résumé : L'ENAC, l'autorité d'aviation civile de l'Italie, a publié la réglementation concernant les systèmes d'aéronef télépiloté (RPAS) dont la masse maximale au décollage est moindre que 150 kg. L'objectif du présent document est d'analyser l'application de prescriptions réglementaires italiennes concernant l'évaluation des risques pour une famille de RPAS. Les résultats de cette analyse, effectuée en collaboration avec l'ENAC, sont comparés à d'autres méthodes disponibles afin de donner une vue d'ensemble très complète sur la faisabilité de missions et les implications opérationnelles au moyen d'une série de cas d'applications réalistes. Des solutions pratiques sont proposées aux fins d'atténuation des risques pour les opérations spécialisées des RPAS.

Mots-clés : système d'aéronef télépiloté, véhicule aérien sans pilote, procédures de certification, évaluation des risques.

Introduction

Unmanned aircraft systems (UAS) have been hugely developed in recent years. In particular, small unmanned aerial vehicles (UAVs) can be used in civil applications, such as agriculture, traffic monitoring, prevention of fires and disaster, search and rescue, environmental research, pollution, monitoring of artistic heritage, and general photography and videos. Many countries have developed regulations to allow UAS integration in their National Airspace Systems. The regulations' basic principle is to give UAS an equivalent level of safety to that of manned aviation.

In December 2013, the Italian Civil Aviation Authority (Ente Nazionale per l'Aviazione Civile, ENAC) published regulations on remotely piloted aircraft systems (RPAS) with maximum take-off mass (MTOM) of less than 150 kg, which came into force at the end of April 2014. The use of the term RPAS is to emphasize that, although not on board, the pilot is always present and has the capability to control the RPAS flight at any time. Indeed, the regulation applies to remotely operated and (or) semiautomatic RPAS and it is not intended to regulate fully-automatic RPAS, as stated in article 2 paragraph 3 of the ENAC regulations: "Moreover, are not subjected to the provisions of this Regulation RPAS that have design features such that the pilot does not have the ability to intervene in the control of the flight".

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The regulation makes a distinction between RPAS with MTOM equal to or more than 25 kg and RPAS with MTOM of less than 25 kg: for the latter, simplified procedures are applied if the operations are not critical.

Noncritical and critical operations are defined in (ENAC 2013). Noncritical operations are those conducted in areas where an impact on the ground will not cause fatal injuries to people on the ground or severe damage to third parties (buildings, infrastructure, etc.) on the ground. Noncritical operations are performed in the volume of space V70, a volume of space of 70 m (230 ft) maximum height above the ground and 200 m in radius. The operator must provide to ENAC a series of documents that state that the system is compliant with the regulation, and the results of risk assessment to motivate the safety of the planned operations, for both critical and noncritical specialized operation.

Several works have been made in assessment of risk for UAS operations. Clothier and Walker (2006) provided a discussion on the definition and application of safety objectives to ensure appropriate requirements for UAS operations. A simple ground fatality expectation model is also used to illustrate the influence of safety objectives variation on the design and operations of UAS. Lum and Waggoner (2011) proposed a risk model for both midair collision and ground collision. The same model is applied in Lum et al. (2011) to assess the risk associated with operating an UAS in a populated area. Weibell and Hansman (2005) introduced the concept of risk mitigation for small UAVs. Size of potential impact area, kinetic energy at impact, and system design of small UAVs decrease the ground fatality risk.

The aim of this paper is the application of Italian regulatory prescriptions for risk assessment to a family of RPAS. The results of this analysis are compared with other available methods, providing a comprehensive insight for mission feasibility and operational implications in a set of realistic application cases. Mitigation factors must be considered to be not too restrictive for both critical and noncritical scenarios.

The paper is organized as follows. Two risk assessment methods are presented in Sect. 2. In Sect. 3, three reference RPAS are described, while a description of two operative scenarios appears in Sect. 4. Section 5 provides the risk assessment results. The paper concludes with discussion on obtained results.

Methods for risk assessment

Many risk assessment methods can be found in the literature. Two risk assessment methods are investigated in this work. The method indicated in JAA/EUROCONTROL (2004) has also been analyzed. The results obtained are too permissive and are not shown in this work.

The method proposed by Dalamagkidis et al. (2012) takes into account:

- area affected by the crash (A_{exp});
- population density (D_{p}); and
- probability of fatal injuries to people exposed to the crash (P_{f}).

RPAS dimensions (wingspan, fuselage length), glide angle (γ), and height and width of an average human determine A_{exp}. Kinetic energy at impact and sheltering (sheltering factor, P_{s}) are used to compute P_{f}. For further details see Dalamagkidis et al. (2012). Sheltering is an important factor considered in this method. Indeed, trees, buildings, vehicles, and other obstacles can shelter a person from the impact, reducing the probability of fatal injuries.

The maximum acceptable probability for on-ground victims per fatal RPAS accident is computed as

$$P = \frac{N}{A_{\mathrm{exp}} D_{\mathrm{p}} P_{\mathrm{f}}} \tag{1}$$

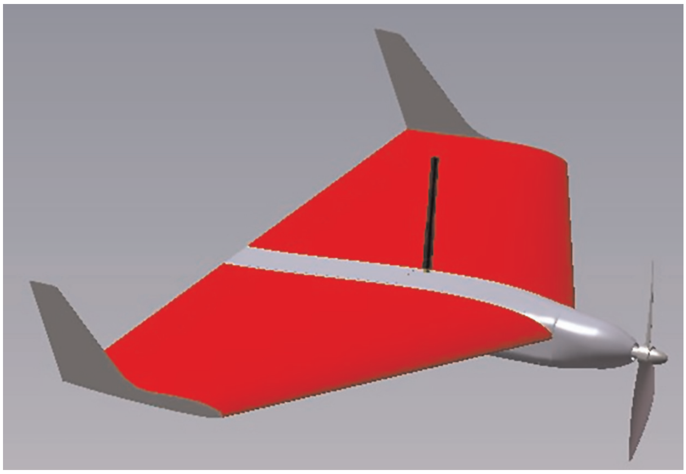
where N is the number of on-ground victims per flight hour and is set equal to 10^{-6} as a safety objective.

The method proposed by ENAC comes from the FAA (2000) and takes into account:

- casualty area of impacting debris (A_{c}); and
- population density (D_{p}).

In this method A_{c} is computed in a different way with respect to A_{exp} from Dalamagkidis et al. (2012): RPAS (or equivalently SAPR in Italian technical literature) maximum dimension (R_{apr}) is used

Fig. 1. MH850.



(i.e., wingspan for fixed-wing aircraft or diagonal wheelbase for multicopters). For further details see FAA (2000). Glide angle is also considered.

The maximum acceptable probability for on-ground victims per fatal RPAS accident is computed as

$$P = \frac{E_c}{A_c D_p} \quad (2)$$

where E_c is the expected casualty and it is set equal to 10^{-6} as a safety objective.

The aircraft

Three reference RPAS developed by MAVTech srl (www.mavtech.eu), a spin-off of Politecnico di Torino, have been considered for the risk assessment. The MH850 is a fixed-wing aircraft, characterized by tailless wing–body configuration, twin non-movable vertical fins at wing tips, and electric propulsion in a tractor configuration (Fig. 1). Wings are made of EPP (expanded polypropilene) thus the aircraft is durable. The wingspan is 872 mm, the fuselage length is 450 mm, the propeller diameter is 230 mm, and the total weight is 1 kg. The Q4-Rotor is a multicopter characterized by four booms and four rotors. The diagonal wheelbase is 1 m and the total weight it 2.9 kg. Finally, the Q8-Rotor is a multicopter characterized by four booms and two rotors mounted coaxially on the end of each boom (Fig. 2). The diagonal wheelbase is 1 m and the total weight it 4.7 kg.

The scenario

Two types of scenarios have been considered for the risk assessment: a noncritical scenario and a critical one. The noncritical scenario is characterized by uniform population density of 25 habitants per square kilometre. The critical scenario is a real case. The area considered is that of Torino Aeritalia Airport (I-LIMA), located in the north–west of the city, on the border between Torino and the town of Collegno. The area is shown in Fig. 3, where two squares are drawn: the red one is 1 km × 1 km, while the green one is 2 km × 2 km. Torino Aeritalia Airport is a promising site for RPAS experimental activities. Flight operations take place in the red square. The site is characterized by different population density and offers different kinds of shelter for people on the ground. Agricultural lands (north) are characterized by low population density and few trees that offer poor shelter; whereas, residential buildings and industrial settlements (south) offer high population density but also high values of sheltering factor. To evaluate the average population density and sheltering factor, the area has been partitioned into nine squares (Fig. 4). For each area, population density (D) and sheltering factor (P_s) are estimated and the average value has been evaluated (see Table 1).

Fig. 2. Q8-Rotor.

Fig. 3. Torino Aeritalia airport (map data: Google, Digital Globe).

Fig. 4. Partition of the flight area (map data: Google, Digital Globe).

Table 1. Estimation of population density (D_p) and sheltering factor (P_s) for critical scenario.

Area	Surface (km^2)	D_p (people/km^2)	P_s
0	1	10	1
1	0.5	10	2
2	0.25	10	3
3	0.5	10	6
4	0.25	5000	12
5	0.5	2000	12
6	0.25	500	12
7	0.5	10	2
8	0.5	10	2
	Weighted average	601.25	4.81

Results

The results presented in this work are based on some hypotheses:

- for MH850 the glide angle is set equal to 45°;
- for QX-Rotor (Q4-Rotor and Q8-Rotor) a vertical impact – crash is considered, thus the glide angle is set equal to 90°;

Table 2. Dalamagkidis et al. (2012) – Risk assessment results in noncritical operations (D_p = 25 people/km^2).

	M (kg)	V (m/s)	Kinetic energy (J)	A_{exp} (m^2)	P_s	P_f	P (1/h)	1/P (h)
MH850	1	42	882	1.451	4	0.255	0.108	9.3
Q4-Rotor	2.9	37	1991	3.665	4	0.397	0.027	36
Q8-Rotor	4.7	37	3227	3.665	4	0.489	0.022	45

Table 3. ENAC – Risk assessment results in noncritical operations (D_p = 25 people/km^2).

	R_{apr} (m)	γ (°)	A_c (m^2)	P (1/h)	1/P (h)
MH850	0.872	45	8.534	0.0047	213
Q4-Rotor	1	90	5.309	0.0075	133
Q8-Rotor	1	90	5.309	0.0075	133

Table 4. Dalamagkidis et al. (2012) – Risk assessment results in critical operations (D_p = 600 people/km^2).

	M (kg)	V (m/s)	Kinetic energy (J)	A_{exp} (m^2)	P_s	P_f	P (1/h)	1/P (h)
MH850	1	42	882	1.451	4.81	0.178	0.006	154.9
Q4-Rotor	2.9	37	1991	3.665	4.81	0.275	0.0016	607
Q8-Rotor	4.7	37	3227	3.665	4.81	0.344	0.0013	759

Table 5. ENAC – Risk assessment results in critical operations (D_p = 600 people/km^2).

	R_{apr} (m)	γ (°)	A_c (m^2)	P (1/h)	1/P (h)
MH850	0.872	45	8.534	0.00019	5132
Q4-Rotor	1	90	5.309	0.0003	3192
Q8-Rotor	1	90	5.309	0.0003	3192

- for MH850 propeller diameter is considered to evaluate A_{exp}, instead of wingspan, because EPP wings can absorb energy during impact by disintegration;
- MH850 kinetic energy is computed considering its maximum operative speed, increased by 40%; and
- QX-Rotor kinetic energy is computed considering freefall velocity from an altitude of 70 m.

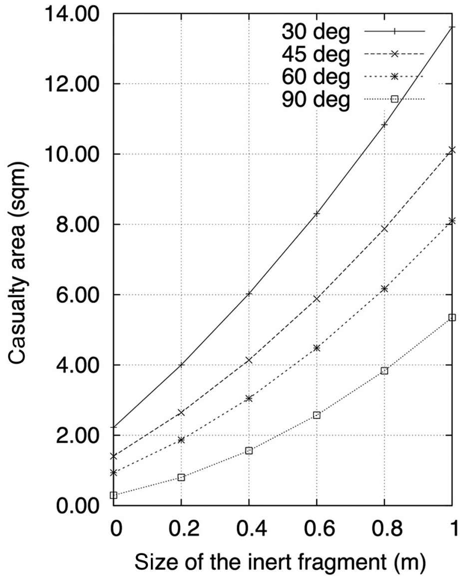
Tables 2 and 3 show risk assessment results in noncritical operations for Dalamagkidis et al. (2012) and ENAC methods, respectively, while results for the critical scenario are shown in Tables 4 and 5. In Dalamagkidis et al. (2008), the term 1/P is defined as the minimum acceptable period between ground impact accidents.

Comments and concluding remarks

According to the tables the method proposed by ENAC is more restrictive with respect to Dalamagkidis et al. (2012) (a difference of an order of magnitude). Furthermore, MH580 is "more dangerous" (higher values of 1/P) than QX-Rotor.

The reason for the discrepancy between the two methods is that the method proposed by ENAC does not consider the mass of the RPAS and sheltering. The new version of the ENAC circular and associated guidelines will introduce the concept of shelter. The mass of the RPAS is used in Dalamagkidis et al. to compute kinetic energy at impact. Together with sheltering factor, the mass plays an important role to determine the probability of fatal injuries to people exposed to the crash. Kinetic energy, together with system design characteristics, are considered in ENAC (2014) only for RPA less than 2 kg to assess the RPA capability to harm a person or cause fatal injuries during impact. Furthermore, the

Fig. 5. Parametric analysis on casualty area as a function of size of the inert fragment (the glide angle is the parameter).



method proposed by ENAC comes from a methodology used to evaluate expected casualty during space launch and reentry missions (space debris). Weights and dimensions of vehicle used for these purposes are not comparable with small RPAS (two orders of magnitude at least) as well as velocity at impact. Moreover, less substantial differences are presented by different human body dimensions used by the methods for computing casualty area.

A series of analyses have been performed on each parameter involved in the maximum acceptable probability. A parametric analysis on casualty area as a function of the size of the inert debris has been performed (Fig. 5), where the glide angle is the parameter.

Casualty area increases very steeply as the size of the inert fragment increase. Casualty area is also strongly affected by glide angle. For reserve design purposes, propeller diameter, scaled by number of rotors, can be used to determine A_c for RPAS characterized by crashable design (EPP or frangible components).

A second parametric analysis has been performed on the trend of the casualty area as a function of the population density (Fig. 6). The maximum acceptable probability for on-ground impact (P) is the parameter.

According to the graph, for a realistic value of $P = 0.01$ (typical value for small RPAS), the lethal crash area tends to nullify for population density up to 100 habitants per square kilometre, thus the dimensions of the RPAS tend to zero. Consequently, if risk mitigation factors are not taken into account, operations on densely populated areas (above 100 people per square kilometre) become unfeasible ($1/P$ too high) for small RPAS.

The proposed solution is to take into account shelter of the area. Starting from the sheltering factor proposed by Dalamagkidis et al. (2012), its values have been qualitatively reviewed in terms of sheltering percentage (from 0% to 100%). The percentage is associated with the type of shelter that trees and (or) buildings may provide to people on the ground (Table 6).

Sheltering percentage must be averaged over the area of operations, buffer zone included (indicatively for a 2 km × 2 km square) and weighted with the population density.

Probability of fatality as a function of the MTOM is presented in Fig. 7. Sheltering percentage is the parameter. The graph is obtained starting from the kinetic energy at impact computed as

(3) $$E_c = \frac{1}{2}MV^2$$

where M is the MTOM and V is the velocity at impact. In this case V is set equal as the freefall velocity from an altitude of 70 m, that is, approximately 37 m/s.

Fig. 6. Casualty area as a function of population density and maximum acceptable probability.

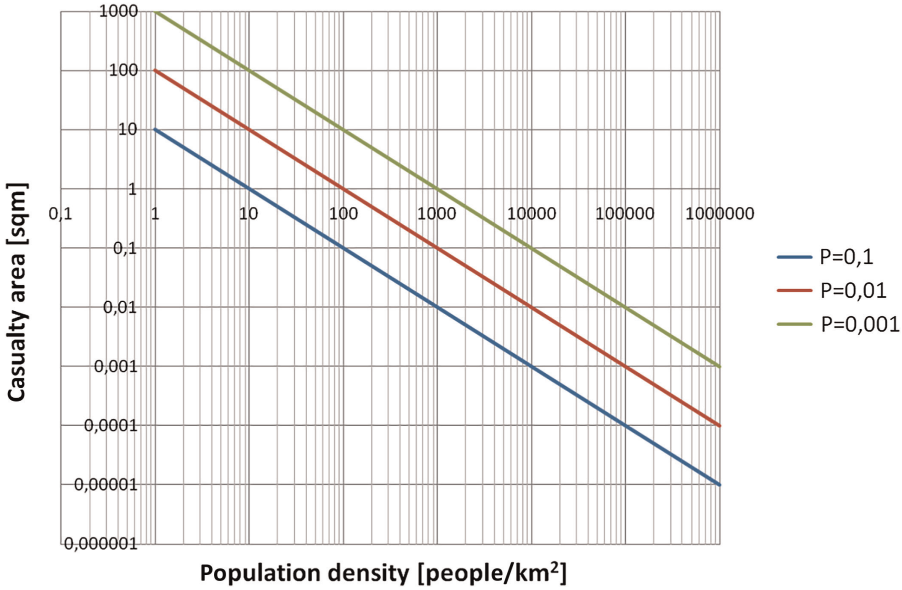
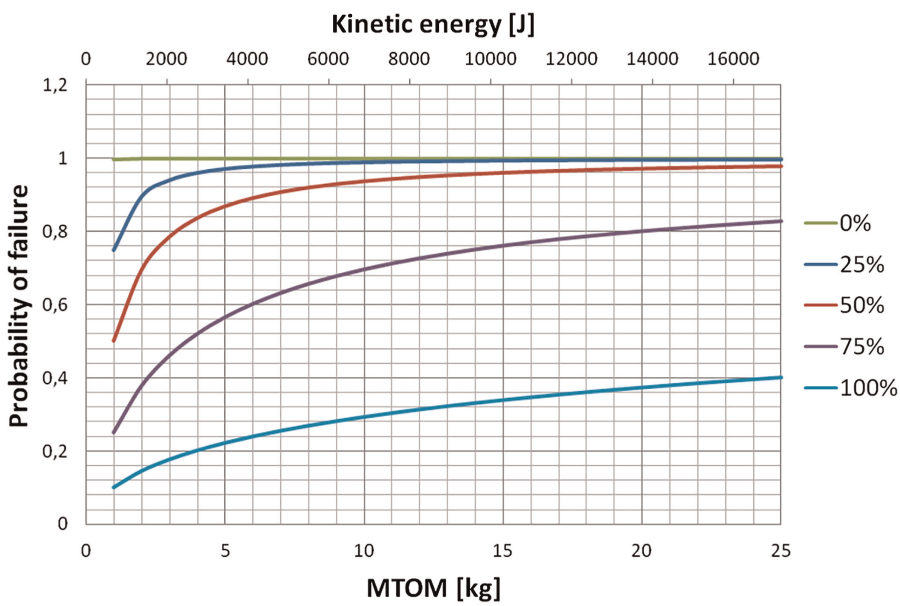


Fig. 7. Probability of fatality as a function of RPAS MTOM and percentage of sheltering, with $V = 37$ m/s.



The solution proposed in ENAC (2014) introduces a probability factor, G, in case of nonhomogeneous population density areas. The probability factor, G, takes into account that RPAS may crash in a specific area. An example is shown in Fig. 8. G is computed for every slice of area as

$$G_i = \frac{\vartheta_i}{2\pi} \tag{4}$$

where ϑ_i (rad) is the subtended angle of the slice of area considered.

Fig. 8. Partition of the area of operations considering the probability factor, G (map data: Google, Digital Globe).

Table 6. Type of area and sheltering related percentage.

Sheltering percentage	Type of area
0	Area without obstacles ($P_f = 1$)
25	Sparse trees
50	Trees and low-rise buildings
75	High-rise buildings (residential area)
100	Reinforced concrete buildings (industrial area)

For each area the maximum acceptable probability is computed as

$$P_i = \frac{E_c}{A_c D_i G_i} \tag{5}$$

where D_i is the average population density of each sector.

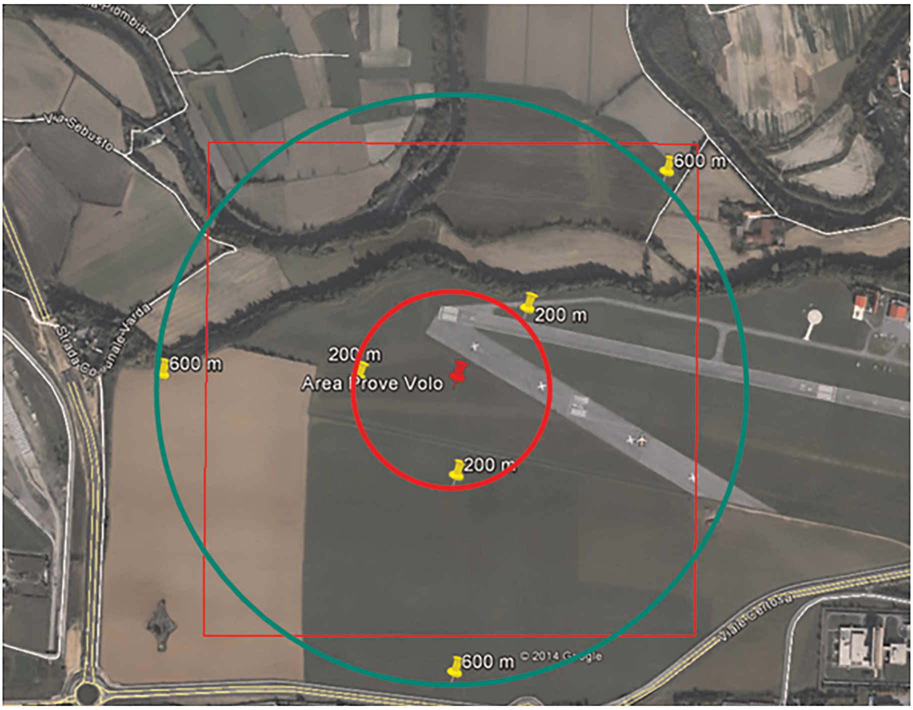
A numerical evaluation has been performed for the critical scenario and results are shown in Table 7. MH850 is considered here.

According to the results, the most critical sector is the first one, in which residential buildings are present. The introduction of the probability factor, G, has halved the term $1/P$ from 5132 h (Table 5) to 2516 h.

Table 7. Risk assessment results using probability factor, *G*.

i	D_i (people/km^2)	ϑ_i (°)	P_i (1/h)	$1/P_i$ (h)
1	2880	$\beta = 37$	3.97×10^{-4}	2516
2	1478	$\gamma = 53$	5.37×10^{-4}	1861
3	504	$\beta = 37$	2.27×10^{-3}	440
4	10	$180 + 2\alpha = 233$	1.81×10^{-2}	55

Fig. 9. Noncritical scenario for Torino Aeritalia Airport. Area of operations (red), buffer area (green) (map data: Google, Digital Globe).



Finally, if the buffer area is chosen accurately according to regulatory prescriptions, the Torino Aeritalia site can be considered a noncritical scenario (Fig. 9). The red circle represents the area of operations with radius 200 m according to volume of space "V70". The green circle represents the buffer area. Buffer area may be overflown in case of emergency landing or SAPR uncontrolled flight and has analogous characteristics as the area of operations. Buffer area is evaluated considering RPAS behavior in case of failure. A maximum buffer area of 600 m radius (a horizontal safety distance of 400 m from the border of the area of operations) can be considered without overfly of congested areas, highways or industrial sites. The safety distance is conservative if we look at a failure mode that causes a multirotor fall from an altitude of 70 m. Considering an initial horizontal velocity of 15 m/s, the multirotor travels 57 m horizontally before crashing into the ground.

As a final comment, the extraordinary job done by Italian aviation authorities allows safe operations in a wide set of scenarios, even if the approach to risk assessment is too restrictive for congested areas. A revision of the estimation procedure, mainly based on sheltering factors, is proposed and validated herein. The introduction of a sheltering factor is mandatory to obtain results in terms of system reliability demonstrable with experimental activities for both critical and noncritical scenarios. This will be considered in the new version of the ENAC Circular and associated guidelines. In case of nonhomogeneous population density, a partition of the area could also be considered. If the scenario is accurately evaluated, in terms of buffer area, it is easy remain iwthin noncritical operations.

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