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METODOLOGIA DI VALUTAZIONE DEL RISCHIO IN OPERAZIONI RPAS PER AUTORIZZAZIONI E PERMESSI DI VOLO NON GEOGRAFICI

GUIDA APPLICATIVA

(GROUND RISK ANALYSIS FOR RPAS OPERATIONS)

Executive Summary (EN)

This guideline describes the principles based on which the quantitative methodology [2] reported in Appendix 1 has been developed to work out the risk for people on the ground during an UAS operation. The ground risk is expressed in terms of the mean expected casualties per mission, which is then compared with established safety objectives. The main parameters utilized to calculate the ground risk are the population density of the of the areas of the operation, the characteristic dimension of the UA, the time of flight and the probability of an out-of-control event which may lead to an uncontrolled flight of the UA or its parts into the ground. A specific implementation procedure of the general methodology, which is valid under simplified assumption, is also described in the present guideline, though the methodology is applicable in situations that are more general. This methodology may be used as an acceptable strategic mitigation for ground risk (M1) to determine the final Ground Risk Class (GRC) within the SORA analysis. In the Appendix 1 of the present guideline, the English version of the complete methodology is attached.

LINEE GUIDA

INDICE

MODIFICHE RISPETTO ALLA PRECEDENTE EDIZIONE	
Para 3	*Aggiornati i riferimenti regolamentari a seguito della emissione dell'Edizione 3 del Regolamento Mezzi Aerei a Pilotaggio Remoto. Aggiornato il testo per tenere conto delle modifiche al Regolamento e, in particolare, dell'introduzione degli scenari standard e dell'analisi SORA.*
Appendice 1	*Allegato in Appendice 1 il documento riportante la metodologia descritta dalla presente Linea Guida, nella versione in lingua inglese.*

RIFERIMENTI REGOLAMENTARI	**Paragrafo**	**Titolo**
Regolamento Mezzi Aerei a Pilotaggio Remoto, Edizione 3 del 3 novembre 2019	*Rif. Para. 3. della presente Linea Guida*	*Rif. Para. 3. della presente Linea Guida*

APPLICABILITÀ'	
APT	***N.A.***
ATM	***N.A.***
EAL	***N.A.***
LIC	***N.A.***
MED	***N.A.***
NAV	***Operatori SAPR***
OPV	***N.A.***
SEC	***N.A.***

1. INTRODUZIONE

Le autorizzazioni o i permessi di volo (PTF) *non geografici* sono autorizzazioni o permessi di volo non strettamente legati ad una specifica area delle operazioni, individuata da precisi riferimenti geografici. Una autorizzazione non geografica o un permesso di volo non geografico non specifica quindi una determinata area geografica al disopra della quale poter condurre le operazioni ma ne specifica, invece, le caratteristiche, ad esempio in termini di densità abitativa, insieme ad alcune modalità operative come i profili di volo o i tempi massimi di sorvolo, definendo in tal modo uno specifico *scenario operativo*. Le autorizzazioni o permessi di volo non geografici permettono di operare su diverse aree geografiche aventi le medesime caratteristiche specificate nello scenario, con le medesime modalità operative.

2. SCOPO

La presente Guida Applicativa ha lo scopo di descrivere i principi su cui si basa la metodologia di analisi del rischio descritta in [2], e riportata Appendice 1, fornendone una procedura applicativa semplificata, applicabile sotto le ipotesi descritte al successivo Paragrafo 5. Ogni scostamento da tali ipotesi o dai criteri sviluppati nella Metodologia dovrebbe essere discusso e concordato con l'Autorità. La presente Guida Applicativa, al pari della metodologia descritta in [2], rappresenta un metodo accettabile di rispondenza, ma non il solo metodo possibile, ai requisiti del Regolamento[1] [1] riportati nel successivo Paragrafo 3. e, in quanto tale, non riveste, di per sé, carattere di obbligatorietà. La metodologia [2] descritta nella presente linea guida può essere utilizzata nell'ambito dell'analisi SORA come possibile mitigazione strategica M1 ad un libello di robustezza Medio o Alto per la riduzione dell'indice di rischio a terra (GRC).

3. APPLICABILITÀ

In generale la metodologia di analisi del rischio descritta in [2] può essere utilizzata nei seguenti ambiti:

(i) per l'ottenimento di un permesso di volo per RPAS con massa operativa al decollo uguale o superiore a 25 kg per gli scopi di ricerca e sviluppo, dimostrazione di rispondenza e operazioni specializzate (Reg. Art. 15.2);

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[1] Per brevità, a meno che sia esplicitamente indicato diversamente, nella presente Guida Applicativa con la parola "Regolamento" o con l'abbreviazione "Reg." ci si riferirà al Regolamento [1] mentre con la parola "Metodologia" ci si riferirà al documento [2].

(ii) per l'ottenimento di una autorizzazione per RPAS con massa operativa al decollo inferiore a 25 kg per lo svolgimento di attività per scopo di ricerca e sviluppo (Reg. Art. 8.10);

(iii) per l'ottenimento di una autorizzazione per RPAS con massa massima al decollo inferiore a 25 kg per lo svolgimento di operazioni specializzate critiche (Reg. Art. 11.1) al di fuori degli scenari standard pubblicati dall'ENAC;

(iv) per l'ottenimento di un certificato di progetto per un RPAS con massa massima al decollo inferiore a 25 kg (Reg. Art. 13.2).

La Metodologia [2] e la presente Linea Guida rappresentano un possibile metodo per implementare la mitigazione strategica[2] M1 del SORA[3] per la determinazione dell'indice di rischio a terra finale (GRC – Ground Risk Class) ad un livello di robustezza Medio o Alto. L'applicazione del SORA è richiesta in modo esplicito dal Regolamento [1] all'Art. 10 comma 5, comma 7 e all'Art. 15 comma 4, comma 7.

La Metodologia [2] rappresenta, infine, uno strumento di analisi utilizzabile dall'operatore per la valutazione del rischio associato alle operazioni per RPAS con massa operativa al decollo inferiore a 25 kg nel caso di operazioni specializzate non critiche (Rif. Reg. Art. 9 comma 3 punto a)).

Le successive Tabelle 1, 2, 3, 4, 5, 6 descrivono in dettaglio in che modo la Metodologia può essere utilizzata, come metodo accettabile, per dare rispondenza a certi requisiti del Regolamento.

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[2] Anche se non l'unica.

[3] Il documento SORA (Specific Operations Risk Assessment) completo degli Annessi è scaricabile dal sito JARUS: http://jarus-rpas.org/publications

TABELLA 1

Schema generale di utilizzo della Guida Applicativa per la rispondenza al Regolamento

RPAS < 25 kg	Attività sperimentale		Tabella 2	Art. 8 comma 10
	Operazioni Specializzate	Non critiche	Tabella 3	Art. 9 comma 3 Art. 9 comma 4
		Critiche	Tabella 4	Art. 10 comma 3 Art. 10 comma 5 Art. 10 comma 7 Art. 11 comma 6
	Certificato di Progetto		Tabella 5	Art. 13 comma 2
RPAS ≥ 25 kg	PTF		Tabella 6	Art. 15. Comma 3 Art. 15. Comma 4 Art. 15. Comma 7

3.1 RPAS CON MASSA MASSIMA OPERATIVA < 25 kg

TABELLA 2

RPA < 25 kg **Attività sperimentale** **(per Ricerca & Sviluppo o Attività sperimentale propedeutica)**			
Art.	**Comma**	**Requisito**	**Rispondenza**
8	10	*L'effettuazione dell'attività per lo scopo "ricerca e sviluppo", è soggetta ad autorizzazione da parte dell'ENAC in accordo a quanto riportato nel sito dell'ENAC.*	Qualora l'attività per scopo di ricerca e sviluppo sia condotta in aree a densità di popolazione non nulla (incluso il *buffer*[4]) la metodologia può essere utilizzata sia per la determinazione del *buffer* (rif. Metodologia Appendice B) sia per l'analisi del rischio a terra.

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[4] Il concetto di *buffer* è definito al Para. 5 – Assunzione **(A2)**

TABELLA 3

RPA < 25 kg Operazioni Specializzate Non Critiche			
Art.	**Comma**	**Requisito**	**Rispondenza**
9	3	*L'operatore è responsabile di : a) sviluppare le procedure operative, ove non fornite dal costruttore, per il tipo di operazione e valutare il rischio ad essa associato; (...)*	La Metodologia può essere utilizzata per valutare il rischio per le terze parti a terra posto dalle operazioni svolte al di sopra di aree caratterizzate da densità di popolazione non nulla, per verificare l'adeguatezza di tale livello di rischio e per definire le condizioni e le limitazioni idonee a garantire, con sufficiente confidenza, il non superamento dei livelli di rischio considerati accettabili. In particolare questo consente di verificare il permanere delle condizioni che fanno ritenere non critiche le operazioni in base alla definizione fornita dall'Art. 9 comma 1. Occorre notare che per essere considerate "non critiche" le operazioni devono essere svolte necessariamente in VLOS (Rif. Art. 9 comma 1), anche se la definizione non vieta che le operazioni non critiche possano essere condotte anche al disopra di aree a densità di popolazione non nulla (seppur non al disopra di aree congestionate, assembramenti di persone o agglomerati urbani); inoltre, al fine di poter continuare ad essere ritenute tali, le operazioni non critiche devono garantire che le aree sorvolate, anche in caso di avarie e malfunzionamenti, abbiano le caratteristiche richieste dalla definizione di operazioni non critiche (Art. 9 comma 1). La Metodologia può essere applicata, quindi, sia per valutare l'adeguatezza del rischio di operazioni non critiche in VLOS effettuate su aree a densità di popolazione non nulla, sia ai fini della determinazione del *buffer* in caso di avarie e malfunzionamenti (rif. Metodologia Appendice B).
9	4	*L'operatore deve possedere e mantenere aggiornata la documentazione che dimostri il rispetto di quanto previsto nel comma precedente*	I criteri, le assunzioni e i metodi di mitigazione utilizzati per implementare la Metodologia dovrebbero essere descritti nelle procedure operative ai fini dell'Art. 9 comma 3 punto c) e in accordo all'Art. 9 comma 4.

TABELLA 4

RPA < 25 kg Operazioni specializzate critiche			
Art.	**Comma**	**Requisito**	**Rispondenza**
10	3	*Le operazioni critiche possono essere condotte ove sia assicurato un livello di sicurezza coerente con l'esposizione al rischio. Il livello di sicurezza di tali operazioni è determinato dall'insieme dei contributi forniti dal SAPR, dal pilota, dalle procedure operative e di gestione delle attività di volo, dalle condizioni ambientali e dagli altri elementi essenziali per determinare un impiego sicuro di tali mezzi, inclusa la corretta attuazione del programma di manutenzione. Il sistema, nel suo complesso, deve pertanto assicurare un livello di affidabilità minimo compatibile con il quadro sopra delineato e adeguato al conseguimento di appropriati livelli di sicurezza in relazione alla tipologia di operazioni. (…).*	La Metodologia può essere utilizzata in generale per dare rispondenza all'Art. 10.3 per operazioni specializzate critiche non rientranti negli scenari standard; inoltre essa tiene conto dell'affidabilità complessiva del sistema RPAS includendo implicitamente tutti i fattori di rischio legati al *design* del sistema, alle operazioni e al pilota. Vedere anche i successivi comma 5 e comma 7.
10	5	*Per le operazioni critiche diverse da quelle effettuate in accordo agli scenari standard, che si svolgono in condizioni VLOS in aree urbane in scenari che non prevedono il sorvolo di persone nell'area delle operazioni e nel buffer, a meno che tali persone non siano indispensabili alle operazioni ed addestrate allo scopo, deve essere dimostrato un adeguato livello di sicurezza tramite l'effettuazione di un'analisi del rischio basata sul documento SORA emesso dal JARUS. (…)*	Nel caso di operazioni critiche in VLOS al di fuori degli scenari standard, la cui analisi del rischio richiede l'applicazione del SORA in base all'Art. 10 comma 5, la Metodologia può essere utilizzata nell'ambito del SORA come possibile mitigazione strategia M1 ad un livello di robustezza Medio/Alto per la determinazione dell'indice di rischio a terra finale GRC (Ground Risk Class).
10	7	*Le operazioni in condizioni BVLOS sono consentite ai SAPR che dimostrino un adeguato livello di sicurezza determinato tramite l'effettuazione di un'analisi del rischio basata sul documento SORA emesso dal JARUS. La conformità a tale requisito è ritenuta soddisfatta ove vengano rispettate le condizioni e le*	Nel caso di operazioni specializzate critiche in BLOS al di fuori degli scenari standard, la cui analisi del rischio richiede l'applicazione del SORA in base all'Art. 10 comma 7, la Metodologia può essere utilizzata nell'ambito del SORA come possibile mitigazione strategia M1 ad un livello di robustezza Medio/Alto per la determinazione dell'indice di rischio a terra finale GRC (Ground Risk Class).

		limitazioni contenute negli scenari pubblicati dall'ENAC.	
11	6	*Per ottenere l'Autorizzazione, l'operatore presenta all'ENAC una specifica domanda nella quale attesta la rispondenza alle sezioni applicabili del presente Regolamento e indica le condizioni e i limiti applicabili alle operazioni di volo previste inclusa, eventualmente, la necessità di operare in spazi aerei segregati. Alla domanda allega la documentazione contenente:* *a) i dati identificativi del SAPR nonché le caratteristiche e le prestazioni tali da garantirne un impiego sicuro (…);* *b) la tipologia delle operazioni che intende svolgere;* *c) l'analisi del livello di rischio associato alle operazioni previste, eseguita al fine di sostanziare la sicurezza delle stesse;* *d) il manuale di volo dell'APR o documento equivalente;* *(…)* *f) le procedure operative relative alle operazioni richieste, inclusa la descrizione delle modalità di valutazione e gestione del rischio;* *(…)*	Le assunzioni utilizzate per implementare la Metodologia e i risultati ottenuti, come ad esempio le caratteristiche dimensionali dell'RPA, la densità di popolazione uniforme massima delle aree sorvolate, le velocità di volo o i tempi massimi di sorvolo di una data area, dovrebbero essere riportate nella documentazione applicabile in termini di limitazioni e condizioni delle operazioni di volo, così come richiesto dall'Art. 11 comma 6, punti a), b), c), d), f), per come applicabile e necessario.

TABELLA 5

RPA < 25 kg **Certificato di Progetto**			
Art.	**Comma**	**Requisito**	**Rispondenza**
13	2	*Il certificato di progetto può essere emesso (…) a condizione che il costruttore abbia: (…) condotto tutte le analisi e le prove necessarie per stabilire le condizioni e limitazioni per dimostrare il livello di sicurezza in funzione dello scenario previsto*	La Metodologia può essere utilizzata per dimostrare un adeguato livello di sicurezza per le terze parti al suolo durante le operazioni al di sopra di aree caratterizzate da densità di popolazione non nulla (incluso il relativo *buffer* – rif. Metodologia Appendice B) previste dagli scenari considerati nella certificazione di progetto, per come necessario (ad esempio nel caso in cui l'RPA non sia inoffensivo).

3.2 RPAS CON MASSA MASSIMA OPERATIVA ε 25 kg

In base all'Art. 15 comma 1 un RPAS con massa massima operativa al decollo uguale o superiore a 25 kg può essere ammesso alla navigazione se è dotato di un Permesso di Volo (PTF) o di un Certificato di Navigabilità Ristretto. Inoltre, in accordo all'Art. 15 comma 2, un PTF può essere emesso per i seguenti scopi:

- Sperimentazione per ricerca e sviluppo, oppure
- Sperimentazione per rispondenza alla base di certificazione, oppure
- Operazioni specializzate.

TABELLA 6

RPA ≥ 25 kg **Permesso di Volo**			
Art.	**Comma**	**Requisito**	**Rispondenza**
15	3	*Il Permesso di Volo specifica le condizioni e/o limitazioni, nell'ambito delle quali devono essere condotte le operazioni, esse includono anche le applicabili limitazioni riguardanti le tipologie delle aree di operazioni.*	La Metodologia può essere utilizzata per stabilire le condizioni e le limitazioni del PTF (qualunque sia lo scopo) nell'ambito delle quali devono essere condotte le operazioni con riferimento, in particolare, alle tipologie di aree sorvolabili nel corso delle operazioni in funzione del livello di rischio posto dalle operazioni stesse. Vedere anche i successivi comma 4 e comma 7.

15	4	*Per ottenere il Permesso di Volo per l'attività sperimentale di cui al comma 2.a) del presente articolo, il richiedente deve presentare domanda all'ENAC fornendo un'analisi del rischio, basata sul documento SORA emesso dal JARUS, atta a dimostrare che l'attività sperimentale che intende svolgere garantisca un accettabile livello di sicurezza. Dalle risultanze dell'analisi del rischio viene identificata la documentazione necessaria per dimostrare la capacità del sistema a svolgere l'attività sperimentale in sicurezza. L'attività sperimentale deve essere condotta in aree a limitato carico antropico, in relazione all'esposizione al rischio. (…)*	La Metodologia può essere inoltre utilizzata, nell'ambito dell'analisi SORA, come possibile mitigazione strategia M1 ad un livello di robustezza Medio/Alto per la determinazione dell'indice di rischio a terra finale GRC (Ground Risk Class). La Metodologia può essere inoltre utilizzata al fine di sostanziare che "l'attività sperimentale deve essere condotta in aree a limitato carico antropico, in relazione all'esposizione al rischio".
15	7	*Per ottenere il Permesso di Volo per operazioni specializzate di cui al comma 2.b) del presente articolo, il richiedente deve presentare domanda all'ENAC fornendo un'analisi del rischio, basata sul documento SORA emesso dal JARUS, atta a dimostrare che l'operazione specializzata che intende svolgere garantisca un accettabile livello di sicurezza. Dalle risultanze dell'analisi del rischio viene identificata la documentazione necessaria per dimostrare la capacità del sistema a svolgere l'operazione specializzata in sicurezza. Il Permesso di Volo è rilasciato dall'ENAC al termine positivo degli accertamenti necessari a verificare che le operazioni previste possono essere condotte con un livello di sicurezza adeguato. (…)*	La Metodologia può essere utilizzata, nell'ambito dell'analisi SORA, come possibile mitigazione strategia M1 ad un livello di robustezza Medio/Alto per la determinazione dell'indice di rischio a terra finale GRC (Ground Risk Class).

4. DETERMINAZIONE DEL LIVELLO DI PROTEZIONE DELLE TERZE PARTI A TERRA

Lo scopo della Metodologia è fornire un criterio di valutazione del rischio per le terze parti a terra dovuto alle operazioni di un RPAS. Il criterio utilizzato tiene conto sia delle caratteristiche del sistema RPAS sia di fattori operativi come la densità di popolazione delle aree sorvolate e i tempi massimi di sorvolo di queste aree. Il criterio si applica a scenari operativi generali non necessariamente vincolati ad una specifica area geografica. L'obiettivo di *safety* da utilizzare per valutare l'accettabilità del rischio calcolato è dato dal parametro E_c definito come **numero medio di *casualties* per missione** accettabile**.** Una *casualty* è definita come una *fatality* (decesso di una persona) o una *serious injury* (incidente grave). E_c rappresenta dunque il massimo rischio accettabile per missione. Il rischio calcolato (R_c) è il **rischio per missione medio**; esso dipende da parametri operativi come la densità di popolazione dell'aerea sorvolata, il tempo di sorvolo di una data area, l'area letale[5] dell'RPA e l'affidabilità complessiva dell'RPAS. Il rischio calcolato R_c non deve essere superiore al rischio accettabile E_c, il che si traduce nella condizione: $R_c \leq E_c$. Calcolando il rischio medio e applicando poi questa condizione è possibile effettuare una valutazione del **livello di protezione** delle terze parti a terra. Per fare ciò vengono definiti due valori numerici[6] per il parametro E_c (ovvero: $E_{c1} = 3 \cdot 10^{-5}$ ed $E_{c2} = 2 \cdot 10^{-4}$ *casualties* per missione) utilizzati, come spiegato successivamente, a seconda della tipologia delle limitazioni e delle condizioni imposte alle operazioni[7]. Il valore più basso dell'obiettivo di sicurezza (E_{c1}) è ritenuto adeguato per minimizzare il rischio per le terze parti a terra nel corso di una missione quando è utilizzato nell'analisi di rischio insieme alle **mitigazioni standard** tipiche di ogni permesso di volo (Rif. [3]). Il valore più alto dell'obiettivo di sicurezza (E_{c2}) rappresenta un limite sotto cui non si dovrebbe scendere ed è ritenuto adeguato per minimizzare il rischio per le terze parti a terra quando è utilizzato nell'analisi di rischio insieme alle **mitigazioni standard** e insieme

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[5] Rif. Para. 7.

[6] Il valori numerici Ec1 ed Ec2 possono variare in base a considerazioni e valutazioni da parte dell'Autorità.

[7] La Metodologia considera due tipologie di mitigazioni chiamate rispettivamente: "*mitigazioni standard*" e "*mitigazioni specifiche*". Entrambe queste tipologie di mitigazioni sono legate allo scenario operativo considerato in quanto contribuiscono a definirlo; esse sono concordate con l'Autorità. Le mitigazioni specifiche definiscono più in dettaglio, rispetto a quelle standard, lo scenario operativo nel quale possono essere svolte le operazioni. Alcuni esempi di possibili mitigazioni specifiche sono: (i) un piano di controllo del territorio, da concordare con gli enti locali interessati, che garantisca il mantenimento di certe caratteristiche come ad esempio una certa densità media di popolazione in una certa zona oppure la segregazione di certe aree, strade, etc. ; (ii) accordi con i servizi di controllo del traffico aereo, la polizia locale, i Vigili del Fuoco, la Guardia Costiera e altri Enti agenti sul territorio; (iii) limitazioni temporali tipo giorno/notte, inverno/estate; (iv) procedure di *emergency recovery* in aree di *recovery* predeterminate; (v) *sheltering*.

alle ulteriori **mitigazioni specifiche**. Il **livello di protezione** delle terze parti a terra viene quindi classificato come BUONO, ADEGUATO o INADEGUATO (Figura 1). Se viene rispettato l'obiettivo E_{c1} (ovvero se $R_c \leq E_{c1}$) il livello di protezione è classificato come BUONO; se viene rispettato l'obiettivo E_{c2} ma non l'obiettivo E_{c1} (ovvero se $E_{c1} < R_c \leq E_{c2}$) il livello di protezione è classificato come ADEGUATO; se, infine, non viene rispettato l'obiettivo E_{c2} (ovvero se $R_c > E_{c2}$) il livello di protezione è classificato come INADEGUATO. Un livello di protezione è ritenuto accettabile quando risulta BUONO oppure ADEGUATO. Se il livello di protezione è BUONO le **mitigazioni standard** sono sufficienti e non sono necessarie mitigazioni specifiche ulteriori. Se invece il livello di protezione è ADEGUATO allora vanno considerate, in aggiunta alle mitigazioni standard, anche ulteriori **mitigazioni specifiche** maggiormente legate alla tipologia delle operazioni e alle specifiche caratteristiche dell'area delle operazioni (Rif. nota 6). Sia le mitigazioni standard sia le mitigazioni specifiche devono essere concordate con l'Autorità a meno di accordi specifici tra il richiedente l'autorizzazione o il PTF e l'Autorità stessa. Se il livello di protezione è INADEGUATO non è raccomandato, in generale, il rilascio di una autorizzazione o di un permesso di volo non geografici[8]. Riassumendo, per ottenere una autorizzazione o un permesso di volo non geografici, in accordo alla Metodologia, occorre:

(1) dimostrare che $R_c \leq E_{c1}$ e definire delle *mitigazioni standard*, oppure

(2) dimostrare che $R_c > E_{c2}$ e definire delle *mitigazioni standard* e delle *mitigazioni specifiche*.

In Tabella 7 è riportata la procedura sopra descritta (vedere anche il diagramma di flusso in Figura 1)

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[8] In tal caso dovrebbero essere definite modifiche tecniche e/o operative o limitazioni aggiuntive in maniera tale da riportare il livello di protezione ad un livello accettabile (ovvero BUONO o ADEGUATO).

TABELLA 7

Procedura di applicazione della Metodologia di analisi del rischio

Step 1	Definisci le mitigazioni standard a livello di progettazione, produzione, operazioni, piloti, e organizzazioni (ad es. di progettazione, di produzione, di manutenzione, di addestramento)
Step 2	Assumi un obiettivo di sicurezza $E_c=E_{c1}$
Step 3	Applica la Metodologia (con $P_c=1$ oppure con $P_c<1$) per calcolare il rischio R_c
Step 4	Confronta in rischio calcolato con l'obiettivo selezionato: $R_c \leq E_c$?
Step 5	Valuta: se $R_c \leq E_c$ allora OK FINE, altrimenti
Step 6	Valuta**:** se $E_{c2}>R_c>E_c$ allora:
Step 6.1	Modifica il progetto, le operazioni e le mitigazioni standard (ad esempio in maniera tale da ottenere una probabilità di caduta $P_c<1$ più piccola della precedente), oppure in alternativa
Step 6.2	Prevedi ulteriori misure di mitigazione specifiche applicabili all'area delle operazioni e scegli un obiettivo E_c tale che: $E_{c1}<E_c \leq E_{c2}$
Step 6.3	Torna allo **Step 3**
Step 7	Valuta: se $R_c>E_{c2}$ allora non è raccomandata l'emissione di una autorizzazioni o PTF non geografici.

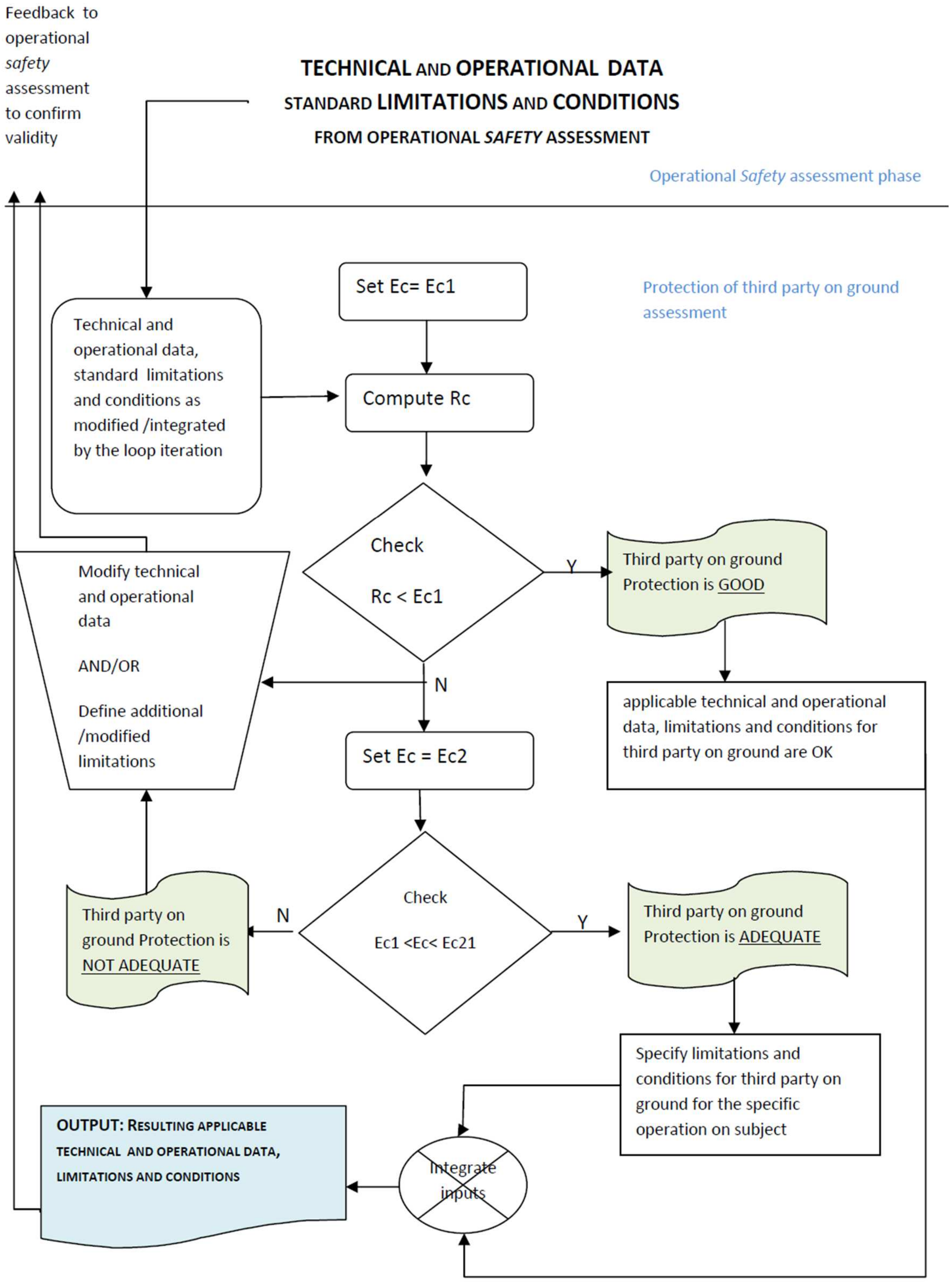

FIGURA 1 – Diagramma di flusso per l'applicazione della Metodologia di analisi del rischio

5. ASSUNZIONI DEL MODELLO DI RISCHIO

Di seguito sono riportate le assunzioni e le ipotesi alla base del modello di rischio utilizzato dalla Metodologia. Qualora tali assunzioni e ipotesi non siano completamente verificate o non siano ritenute adeguate per il concreto caso in esame, l'utilizzo del modello di rischio dovrà essere discusso e concordato con l'Autorità.

(A1) *Densità di popolazione*. L'area delle operazioni viene suddivisa in sotto aree caratterizzate da densità di popolazione uniforme[9] $A_i \; (i = 1, \dots, m)$.

(A2) *Buffer*. Il *buffer* corrispondente ad una specifica area delle operazioni è definito come la zona esterna all'area nominale delle operazioni[10] entro cui l'RPA può cadere in caso di avarie o malfunzionamenti singoli[11] che avvengano all'interno dell'area nominale delle operazioni. Una certa zona di *buffer* è associata ad una certa area (o sotto area) delle operazioni con densità di popolazione uniforme se l'RPA può cadere all'interno di quella zona di *buffer* uscendo da quella specifica area (o sotto aerea) delle operazioni (Figura 2). Vi possono essere quindi diverse zone di *buffer* associate a diverse aree delle operazioni. Ogni zona di *buffer* associata ad una area delle operazioni (con densità di popolazione uniforme) è supposta avere la stessa densità di popolazione dell'area delle operazioni cui è associata[12].

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[9] Rif. Para. 8.

[10] L'area nominale delle operazioni è l'area al di sopra della quale sono autorizzate le operazioni normali. In caso di emergenza è possibile la fuoriuscita dall'area nominale delle operazioni ma non la fuoriuscita dall'area di buffer (a meno di eventi poco probabili dovuti ad avarie o malfunzionamenti multipli). Nella presente Guida Applicativa, per brevità, qualora non diversamente specificato, con l'espressione "area delle operazioni" si intende "area nominale delle operazioni".

[11] La fuoriuscita dal *buffer* in caso di avarie o malfunzionamenti doppi o multipli è ritenuta generalmente accettabile, a meno che la probabilità di fuoriuscita dal *buffer* per tali cause multiple non sia trascurabile; in tal caso eventuali misure di mitigazione dovranno essere concordate con l'Autorità.

[12] Questa assunzione è giustificata dal fatto che mediante la Metodologia viene determinato un tempo massimo Ti di sorvolo di una certa area delle operazioni Ai con densità di popolazione uniforme Di in modo che il numero medio Ri di *casualties* durante le operazioni sopra l'area Ai nel tempo Ti sia pari a $Ri{=}PciAciDi$ dove Pci è la probabilità di cadere a terra durante la fase di volo al disopra dell'area Ai e Aci è l'area letale nella fase di volo considerata (rif. Para. 9). Poiché per la definizione di *buffer* "associato ad una data area delle operazioni di densità di popolazione uniforme", in caso di avaria o malfunzionamento nella fase di volo al di sopra dell'area Ai vi è la possibilità che l'RPA cada all'interno dell'area di buffer associata (Bi), per la consistenza del modello adottato, il *buffer* Bi dovrà avere la stessa densità di popolazione Di dell'area Ai. Se così non fosse e se, ad esempio, il *buffer* associato Bi avesse una densità di popolazione maggiore, in caso di caduta dell'RPA all'interno di esso il numero medio di *casualties* sarebbe maggiore di quello calcolato considerando la densità Di. L'assunzione **(A2)** potrebbe essere verificata mediante una opportuna delimitazione delle aree nominali delle operazioni.

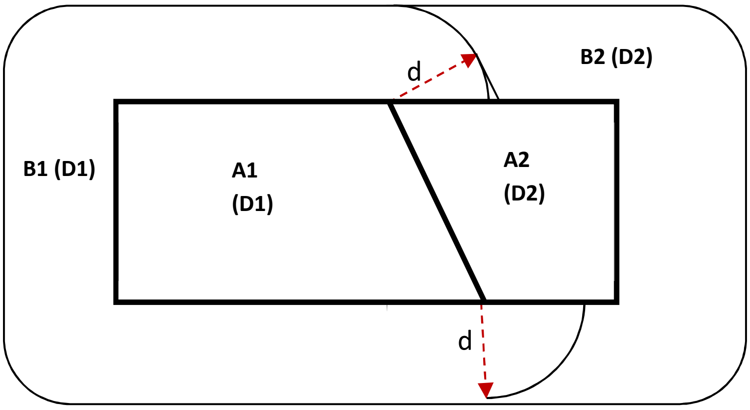

FIGURA 2 – Esempio di definizione delle zone di buffer B1 e B2 associate alle delle operazioni A1 e A2 di densità di popolazione uniforme rispettivamente pari a D1 e D2 (con D1<D2). Si è supposto che in caso di escursione dalle aree nominali delle operazioni A1 e A2 l'RPA possa percorrere in senso rettilineo una distanza massima d prima di cadere a terra. Le due zone di buffer B1 (di densità minore D1, come l'area A1) e B2 (di densità maggiore D2, come l'area A2) sono state determinate imponendo, conservativamente, che un'escursione dell'RPA dall'area A1 a bassa densità (D1) non lo porti a cadere nella zona di buffer B2 a densità maggiore (D2) in quanto in tal caso verrebbero violate le ipotesi del modello perché il rischio calcolato legato al sorvolo dell'area A1 (P_{c1}*A_c*D1) sarebbe inferiore a quello effettivo (P_{c1}*A_c*D2). D'altro canto una escursione dalla zona ad alta densità A2 all'interno del buffer a bassa densità B1 può essere accettata in quanto in tal caso il rischio calcolato legato al sorvolo dell'area A2 (P_{c2}*A_c*D2) sarebbe superiore a quello effettivo (P_{c2}*A_c*D1) – condizione conservativa.

(A3) *Probabilità di caduta.* La probabilità di caduta P_c dell'RPA è la probabilità che si verifichi un evento (dovuto sia a cause tecniche sia a cause operative) che porti ad una perdita di controllo dell'RPA e ad una sua conseguente caduta incontrollata a terra. Tale probabilità è considerata uniforme[13]. In base a tale assunzione la probabilità $P_c^{(j)}$ di avere un evento che porti ad una caduta incontrollata a terra nella j-esima fase di volo ($j = 1, \dots, N$ dove N è il numero di fasi di volo in cui è stata suddivisa la missione[14]) è la stessa per ogni fase di volo j, ovvero: $P_c^{(1)} =$

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[13] Nel caso in cui l'assunzione **(A3)** di probabilità uniforme su tutte le aree sorvolate nel corso della missione non possa essere assunta perché non giustificata o perché ritenuta comunque non adeguata, il modello di rischio da utilizzare nell'analisi deve essere quello fornito dalla formula (21) di [2] o dalla formula (40) di [2] nel caso in cui l'ipotesi di uniformità possa essere ritenuta ancora valida all'interno di ogni singola fase di volo.

[14] Occorre notare che ad una certa fase di volo j (j=1,…,N) possono corrispondere in generale diverse aree delle operazioni di densità di popolazione uniforme. Si pensi ad esempio ad una fase di crociera in cui l'RPA sorvola aree a diversa densità di popolazione.

$P_c^{(2)} = \cdots = P_c^{(N)} = P$. In tal caso la probabilità di caduta nel corso dell'intera missione è pari a $P_c = N \cdot P$.

(A4) *Area letale.* L'area letale di un RPA può essere definita come la sua impronta letale efficace a terra in caso di caduta incontrollata dell'RPA (Rif. Para. 7); essa può variare durante il volo a causa di versi fattori come il consumo di carburante, il cambiamento di geometria o il differente angolo di volo all'impatto (Rif. Para. 7). Si assume che le aree letali A_{ci} relative al volo al disopra delle varie aree operative $A_i \ \ (i = 1, \dots, m)$ siano tutte uguali[15], ovvero: $A_{c1} = A_{c2} = \cdots = A_{cm} = A_c$. L'area letale A_c del'RPA è quindi considerata costante durante tutto il volo.

6. STIMA DELLA PROBABILITÀ DI CADUTA

La probabilità di caduta P_c nel corso della missione può essere stimata mediante vari metodi; di seguito se ne riportano alcuni.

i) Stima basata sulla affidabilità del progetto (sia dei sistemi che delle strutture) con ulteriori considerazioni che permettano di passare dalla affidabilità del sistema legata ai soli aspetti progettuali alla affidabilità complessiva del sistema dovuta, oltre che a cause progettuali, anche a cause operative, produttive, manutentive etc. Ad esempio se N_{ops} è il numero delle occorrenze registrate di perdita di controllo (con conseguente impatto a terra) dovute a cause operative, $N_{failure}$ è il numero delle occorrenze registrato dovuto a cause tecniche (per avarie o malfunzionamenti di sistemi o strutture) e se $N_{tot} = N_{ops} + N_{failure}$ è il numero totale delle occorrenze registrate, in alcuni casi potrebbe essere noto che il numero di eventi dovuti a cause tecniche può essere considerato come una certa percentuale nota $k = \frac{N_{failure}}{N_{tot}}$ degli eventi totali. In tal caso è possibile esprimere la probabilità P_c in maniera proporzionale alla probabilità di un evento catastrofico dovuto a cause tecniche come: $P_c = P_{failure}/k$. I dati di affidabilità dei componenti utilizzati per la stima della probabilità $P_{failure}$ dovrebbero essere sufficientemente accurati.

ii) Stima basata sui dati storici di volo dell'RPAS considerato (o di RPAS simili) operante in scenari uguali o simili a quelli considerati, in maniera da contare sempre gli eventi occorsi in condizioni operative paragonabili. Ad esempio, indicando con n il numero degli eventi di

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[15] Una scelta conservativa consiste nel considerare nel calcolo del rischio l'area letale massima tra quelle associate alle varie fasi di volo sopra le zone di densità Di, ovvero: AC= Ac1, , Acm .

caduta incontrollata a terra avutisi nel corso di un numero N_{miss} di missioni simili già effettuate, la probabilità P_c può essere stimata come[16]: $P_c = \frac{(n+1)}{(N_{miss}+2)}$.

iii) In mancanza di informazioni è sempre possibile assumere conservativamente: $P_c = 1$.

7. AREA LETALE

L'area letale A_c di un RPA è quell'area tale per cui ogni persona al suo interno subirebbe almeno un danno grave (*casualty*) a causa dell'impatto diretto con l'RPA, con sue parti o detriti proiettati o perché investita da un'onda di pressione pericolosa causata da una esplosione (danno al timpano); A_c può quindi essere considerata come l'impronta efficace a terra dell'RPA in caso di *crash.* L'area letale A_c (espressa in piedi quadrati, ft^2) può essere determinata mediante la seguente formula[17] (che assume un angolo di inclinazione della traiettoria all'impatto pari a 45°):

$$A_c = 84(1 + 0.5 \cdot L) + 22(1 + 0.5 \cdot L)^2 + 5.12 \cdot f \cdot (V)^{\frac{2}{3}} \tag{1}$$

Dove L è la dimensione massima dell'RPA espressa in piedi $[ft]$, V è il volume di carburante in litri e f è la probabilità stimata che si abbia l'esplosione del serbatoio di carburante all'impatto (f è quindi un coefficiente che può variare tra zero ed 1).

8. DENSITÀ DI POPOLAZIONE

I dati per stimare la densità di popolazione di una zona dovrebbero essere ottenuti da un *data base* riconosciuto dall'Autorità. La zona delle operazioni viene suddivisa in regioni caratterizzate da densità di popolazione uniforme a meno di diverse considerazioni legate alla specificità del profilo di volo (ad esempio nel caso di volo rettilineo a velocità costante) da concordare con l'Autorità. Un criterio possibile per considerare la una certa regione dell'area delle operazioni come avente densità di popolazione uniforme è che lo scarto quadratico medio della densità di popolazione su questa regione sia inferiore ad 1 abitante per km^2.

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[16] Stima bayesiana.

[17] La formula (1) dell'area letale è definita in [2] secondo criteri conservativi. Diverse espressioni dell'area letale Ac possono essere concordate con l'Autorità ed utilizzate.

9. APPLICAZIONE DEL MODELLO DI RISCHIO E DEFINIZIONE DEL PROFILO DI MISSIONE

In generale il numero medio di *casualty* per missione[18] R_c, cioè il rischio calcolato per missione, non deve superare il valore massimo accettabile E_c (obiettivo di *safety*). Il rischio R_c è calcolato come la probabilità che l'RPA cada a terra in maniera incontrollata *nel corso della missione*[19] P_c moltiplicata per il numero medio di persone N_c all'intero dell'area letale dell'RPA A_c, ovvero: $R_c = P_c \cdot N_c$. Nel caso in cui l'area delle operazioni abbia densità di popolazione uniforme D, il numero medio di persone N_c all'interno dell'area letale è dato dal prodotto della densità di popolazione D moltiplicata per l'area letale, ovvero: $N_c = A_c \cdot D$. Deve essere rispettata pertanto la seguente condizione: $R_c = P_c \cdot A_c \cdot D \leq E_c$. Nel caso in cui l'area delle operazioni non abbia una densità di popolazione uniforme[20] è sempre possibile suddividere tale area in un certo numero di aree $A_1, A_2, \dots A_m$ cui vengono associate, rispettivamente, le densità di popolazione uniformi: D_1, D_2, … , D_m e le probabilità di caduta[21]: $P_{c1}, P_{c2}, \dots, P_{cm}$. Il rischio totale R_c sarà allora calcolato come la somma dei rischi relativi a tutte le aree sorvolate di densità uniforme. Le condizioni da verificare diventano: $R_c = P_{c1}A_cD_1 + \cdots + P_{cm}A_cD_m \leq E_c$ con la condizione sulle probabilità: $P_{c1} + \cdots + P_{cm} = P_c$. Nel caso in cui la probabilità di caduta per missione sia distribuita in maniera uniforme sulle aree sorvolate, in assenza di migliori elementi di valutazione (come informazioni specifiche, analisi, sperimentazioni dedicate, esperienza su casi simili, dati di letteratura, etc.) è possibile assumere le probabilità di caduta $P_{c1}, P_{c2}, \dots, P_{cm}$ proporzionali, rispettivamente, ai tempi di sorvolo $T_1, T_2, \dots, T_m$ delle aree $A_1, A_2, \dots A_m$. Tale scenario è coerente, ad esempio, con una situazione in cui il contributo principale alla perdita di controllo dell'RPAS deriva da guasti sistematici (inclusi errori operativi o comunque che si ripetano con indipendenza dalla

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[18] Il modello di rischio non cambia qualora si esprima l'obiettivo di *safety* in termini di numero medio di *casualties* per ora di volo invece che per missione. In generale l'obiettivo di *safety* espresso per ora di volo avrà un valore numerico diverso da quello espresso per missione, in modo che sia comunque coerentemente preservato il valore medio di *casualties* per missione. Qualora si voglia passare da un obiettivo di *safety* per missione ad un obiettivo di *safety* per ora di volo occorrerà ipotizzare una **durata media rappresentativa** della missione. Ad esempio Se Ec=3·10-5 *casualties* per missione e la durata media rappresentativa della missione è pari a 10 minuti, l'obiettivo di *safety* in termini di ore di volo diventa: 3·10-5 *casualties*/missione x 6 missioni/FH = 1.8·10-4 *casualties*/FH.

[19] La probabilità di perdita di controllo con conseguente impatto a terra è espressa in termini di affidabilità complessiva del sistema cioè come probabilità di un evento che comporti la caduta incontrollata a terra dell'RPA, sia esso dovuto a *failure* del sistema, a suoi malfunzionamenti o a cause operative, di produzione, di manutenzione, etc.

[20] In mancanza di specifiche linee guida il criterio di uniformità della densità di popolazione nell'area delle operazioni e i conseguenti criteri di suddivisione dell'area nominale delle operazioni devono essere concordati con l'Autorità.

[21] Pci è la probabilità che l'RPA cada in maniera incontrollata sull'area Ai.

durata temporale). Poiché tipicamente la probabilità di caduta è più alta nelle fasi di decollo e atterraggio il modello basato sulla diretta proporzionalità della probabilità di caduta dal tempo di sorvolo è adatto agli scenari in cui il decollo e l'atterraggio dell'RPA avvengono in aree segregate e non popolate (ad eccezione del personale necessario per le operazioni). Sotto queste ipotesi la probabilità di caduta P_{ci} nell'area A_i si esprime come: $P_{ci} = \frac{P_C \cdot T_i}{T}$ dove T è tempo totale di volo nel corso della missione. La condizione di rischio da imporre diventa in tal caso[22] (modello semplificato):

(2)
$$D_1 \cdot T_1 + \cdots + D_m \cdot T_m \leq (E_C \cdot T)/(P_C \cdot A_C)$$

La precedente condizione deve essere risolta insieme alle naturali condizioni di congruenza: $T_1 + \cdots + T_m = T,\ T_1 \geq 0,\ \ldots\ , T_m \geq 0$ che esprimono il fatto che la somma dei tempi parziali di sorvolo delle aree deve essere uguale al tempo totale di missione e che i tempi parziali di sorvolo devono essere positivi o nulli. La condizione (2) permette di pianificare la missione in maniera tale che l'RPA voli per un tempo massimo T_1 sopra l'area A_1 di densità uniforme D_1, per un tempo T_2 sopra l'area A_2 di densità uniforme D_1 etc. con un accettabile livello di rischio[23].

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[22] Le densità di popolazione sono espresse in numero di abitanti per km^2; i tempi sono espressi in secondi, minuti od ore; Pc è un numero puro compreso tra zero ed uno; L'area Ac è espressa in km^2 e l'obiettivo di sicurezza Ec è espresso in numero di *casualties* per missione. In ogni caso occorre porre attenzione alla congruenza delle unità di misura dei vari parametri che compaiono nella formula (2).

[23] E' importate porre attenzione al fatto che il valore di Pc deve essere rappresentativo di una **missione tipica avente una certa durata media** T. Qualora cambi la tipologia della missione oppure il tempo di volo complessivo della missione T, la probabilità complessiva di caduta nel corso della missione (Pc) dovrebbe essere rivalutata in quanto potrebbe cambiare anch'essa di conseguenza. Ad esempio se il tempo totale di volo T aumenta anche Pc in generale aumenta nelle ipotesi di distribuzione uniforme nelle varie fasi di volo e quindi non è detto in generale che il secondo termine della (2): EcTPcAc aumenti anch'esso. Quindi occorre tenere presente che in generale un allungamento del tempo di volo T può far cambiare il valore di della probabilità di caduta Pc durante la missione.

Esempio

Consideriamo come esempio applicativo il caso di un RPA, avente un'area letale Ac, che debba effettuare una missione della durata di 1 ora al disopra di un'area delle operazioni che viene suddivisa in tre aree di densità di popolazione uniforme D0, D1, D2. Vogliamo definire i tempi massimi di sorvolo T0, T1, T2 delle tre aree in modo da verificare la condizione (2). Sia:

T=60 min

Ac=333.75 $m^{\wedge 2}$=3.3375E-4 km^2

Pc=0.1

Ec=2E-4

Kc=Ec/(Pc*Ac)=6

D0=0 abitanti/km^2 (area non popolata)

D1=10 abitanti/km^2

D2=5 abitanti/km^2

Applicando la (2) si ha:

$D1*T1+D2*T2 \leq Kc*T=6*60=360 \rightarrow 10*T1+5*T2 \leq 360 \rightarrow 2*T1+T2 \leq 72$

con:

T0+T1+T2=T

$T0 \geq 0, T1 \geq 0, T2 \geq 0$

Scegliamo ad esempio[24] T0=24 min. Allora si dovrà avere:

$T1+T2=T-T0=60-24=36$ min $\rightarrow T2 = 36-T1$

che sostituita nella disuguaglianza fornisce:

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[24] Tale scelta dipenderà dalle esigenze della missione.

$2*T1+36-T1 \leq 72 \rightarrow T1+36 \leq 72 \rightarrow T1 \leq 72-36=36$ min

Scegliamo ora T1 in modo che sia verificata quest'ultima condizione, ad esempio sia: T1=12 min. Allora si avrà di conseguenza:

$T2=36-T1=36-12=24$ min

In conclusione otteniamo: T0=24 min, T1=12 min, T2=24 min. L'obiettivo di sicurezza Ec=2E-4 viene quindi verificato (nel rispetto delle assunzioni poste alla base del modello) pianificando le operazioni di volo in modo tale che, nell'ambito della missione di 1 ora, l'RPA operi per un tempo minimo[25] T0=24 minuti al disopra di un'area disabitata (D0=0 abitanti /km^2) per un tempo massimo T1=12 minuti sopra l'area di densità di popolazione D1=10 abitanti/km^2 e per un tempo massimo T2=24 minuti al disopra dell'area di densità di popolazione di 5 abitanti/km^2.

10. RIFERIMENTI

[1] ENAC, Regolamento Mezzi Aerei a Pilotaggio Remoto, Edizione 3 del 3 novembre 2019

[2] ENAC, *Metodologia di valutazione del rischio in operazioni RPAS per autorizzazioni e permessi di volo non geograf*ici, Edizione 1, 10 dicembre 2015. (*A methodology for evaluating the level of protection of 3rd parties on ground during RPAS operations,* Edition 1_EN, Jan. 2016 – **Appendix 1**)

[3] ENAC Circolare NAV-32 D, Permessi di Volo e Attività Sperimentale

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[25] Nel caso in cui si operi su aree disabitate, con densità di popolazione nulla, non si aumenta il rischio per le terze parti a terra anche nel caso in cui il tempo di sorvolo sopra le aree disabitate aumenta rispetto a quello minimo calcolato, purché l'RPA cada sempre in aree non popolate in caso di avarie o malfunzionamenti. Per tale motivo il tempo T0 di 245 minuti può essere in questo esempio considerato un tempo *minimo* di sorvolo.

11. ACRONIMI

FH	Flight Hours
GRC	Ground Risk Class
M1	Mitigazione strategica per il rischio a terra, così indicata nello Step #3 del SORA, per la determinazione dell'indice GRC finale.
PTF	Permesso di Volo
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System (SAPR)
SAPR	Sistema Aeromobile a Pilotaggio Remoto
SORA	Specific Operations Risk Assessment
UAS	Unmanned Aircraft System
UA	Unmanned Aircraft
VLOS	Visual Light Of Sight

APPENDIX 1

A methodology for evaluating the level of protection of 3rd parties on ground during RPAS operations

(Edition 1_EN, Jan. 2016)

A methodology for evaluating the level of protection of 3rd parties on ground during RPAS operations

A. Rapaccini [1], *G. Di Antonio* (1)

1. Foreword

RPAS operations might need to be authorized. In that aim, the level of protection towards third parties on ground might need to be evaluated. The proposed methodology describes a mean to evaluate such level, based on RPAS characteristics and specific characteristics of areas to be over-flown in term of population density and fight times. The methodology on subject does not require to specify the specific coordinate of the area overflown by RPAS operation to be authorized; areas in fact are defined by parameters relevant to population density and not by specific coordinates, thus increasing the flexibility of the validity of the authorization.

2. Objective

The objective of this paper is to provide criteria to evaluate the risk posed by RPAS operations to third parties on ground, defining a methodology to compare it to different thresholds of acceptability. This paper proposed as well the value of thresholds of acceptability, giving substantiation for the proposal. Depending of the result of the comparison between the risk posed by RPAS operations and the thresholds of acceptability, the level of protection offered by the relevant RPAS operations to third parties on ground is judged accordingly.

The methodology gives, as output, a qualitative result of the level of protection in term of GOOD, ADEQUATE or NOT ADEQUATE, though it is based on quantitative computations that allow an easy and progressive standardization among various NAAs.

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[1] ENAC *(Italian Civil Aviation Authority) – Airworthiness Regulation Department*

Levels of protection judged as GOOD or ADEQUATE represent premises to minimize risks posed by that RPAS operations to levels that are acceptable for the authorization though, by themselves, are not enough to assure the safety of the RPAS operations, which should be assessed in the frame of the general risk assessment (i.e. SORA - operational risk assessment for category B RPAS operations – methodology).

Different values of acceptability threshold might be defined as well by different Regulatory Authority without impairing the validity of the proposed methodology nor the use of this paper.

3. Applicability

Methodology described in this paper is to be used in the frame of the SORA risk assessment (operational risk assessment for category B RPAS operations) to get authorization for RPAS operations. Protection of airspace users are out of the scope of this methodology. Protection of infrastructure and/or environment are out of scope as well.

Methodology proposed by the paper is not to be used in the frame of type certification program nor in the frame of restricted type certification program unless specific agreement with the Competent Authority.

4. References

[1] ENAC, Regolamento Mezzi Aerei a Pilotaggio Remoto (RPAS Regulation)

[2] FAA AC 431.35-1 *Expected Casualty Calculations for Commercial Space Launch and Reentry Missions* (currently superseded by the FAA *Flight Safety Analysis Handbook*, Version 1.0)

[3] UE Commission, *Roadmap for the integration of civil Remotely-Piloted Aircraft Systems into the European Aviation System* – Final Report, June 2013, Annex 3

[4] ICAO *Safety* Report 2014 Edition, Accident Records: 2009–2013 Scheduled Commercial Flights

[5] ENAC Circolare NAV-32D, *Permessi di volo e attività sperimentale*

[6] JARUS, CS-LURS, *Certification Specification for Light Unmanned Rotorcraft System*

5. Overview on the methodology and the relevant criteria

The proposed risk analysis for protecting the 3rd parties on ground, that is the object of this document, has been set in the framework of the more general operational safety assessment, depicted in Figure 1, to be carried out for the aim of issuing an RPAS authorization or permit to flight.

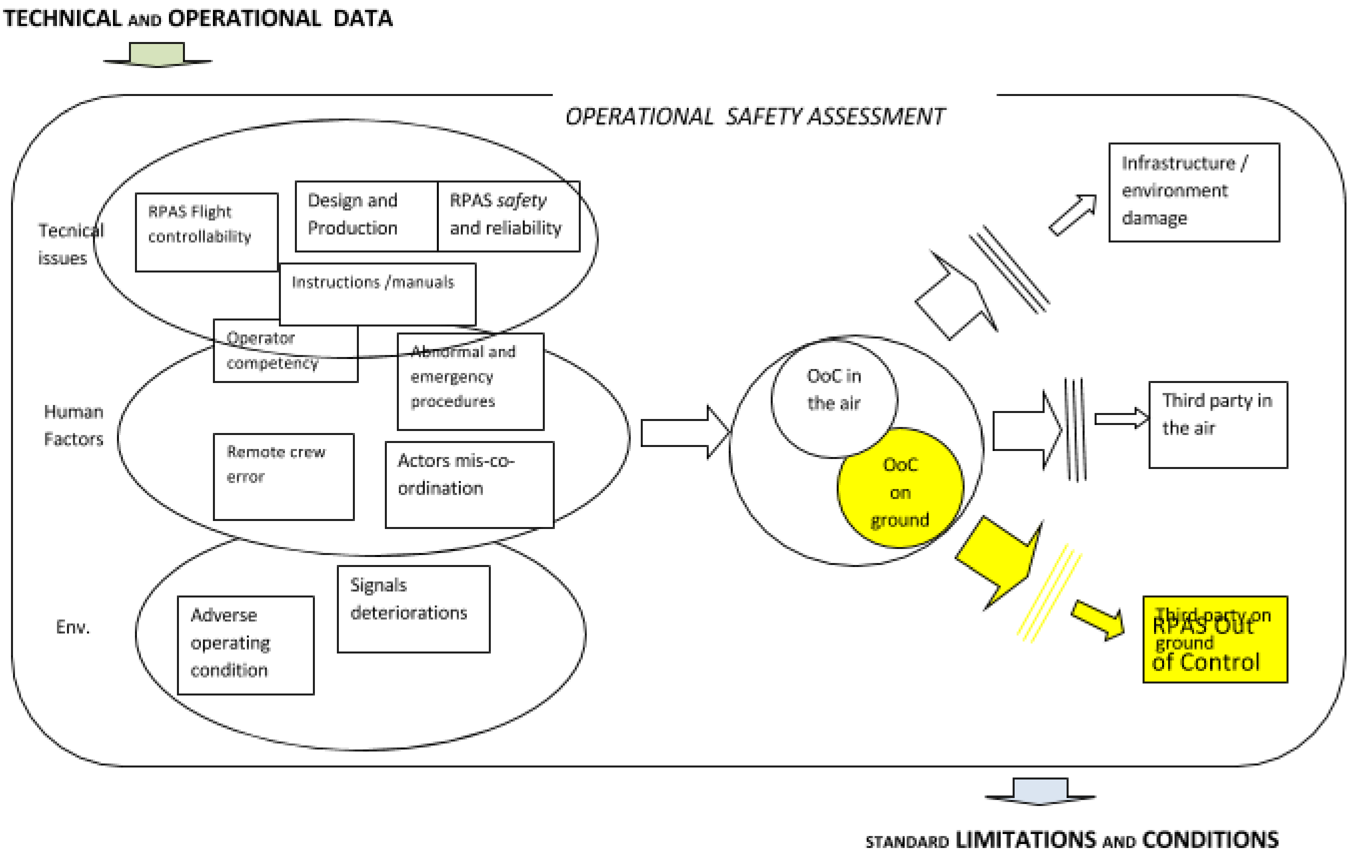

Figura 1 – Operational Safety Assessment

With reference to the generic bow tie of the operational risk assessment of figure 1 (that is intended to sketch a tensed view of the SORA bow tie), this paper focuses on the link between the thread represented by the loss of control of RPAS, on (leading to) ground, and the possible effect on third party on ground, in order to support the definition of the level of protection offered by RPAS operation towards the third parties on ground.

In order to evaluate the level of protection offered by operations on subject, it is necessary to define one or more safety objectives as comparison thresholds. The safety objective considered by this methodology is represented by the parameter **Ec**, defined as **mean value of casualties per mission that can be accepted**. Ec stands conceptually for the maximum risk per mission that can be accepted.

Moreover, it is necessary to compute the **mean value of the risk per mission** as a function of operational parameters as population density of areas that are overflown, of the flight time over a specific area and of RPAS characteristics in term of its lethal area and RPAS reliability.

Risks to third parties on ground can be controlled by acting on those parameters, mainly controlling (and reducing, when necessary) the probability of crash on ground, the flight time over a specific area so to reduce the probability to crash on it, and the effect of an impact on ground in term of expected resulting casualties.

The probability of having the RPAS out of control leading to a crash on ground it is expressed in term of **RPAS reliability**, i.e. in term of probability of a crash on ground of the whole system as effect of any causes, that might be technical systems reliability, malfunctions, human errors, production issues, maintenance issues, environmental issues and so on.

Possible effects of the impact on ground are evaluated as number of casualties following the impact of the RPAS or its parts inside an area; such number of casualties is a function of the RPAS lethal area and of the population density in that area.

RPAS lethal area is made both by the contribution of the direct impact of the RPA and its detached parts with people, both by the effect of the pressure wave caused by a possible explosion following the impact.

As far as population density is concerned, it is foreseen the case that the population density inside overflown areas is uniform as well as not uniform, defining how to **deal** with those two cases.

It worth's noting that while Ec is a figure (conceptually a limit threshold) defined by the Regulatory Authority as acceptable based on defined criteria, the risk Rc is the output of computations based on RPAS and operations characteristics, as defined in this paper, and hence it should be computed and determined by the Operator seeking for RPAS operations authorization, with the support of the designer or/and the manufacturer if necessary.

The quantitative comparison between the computed mean risk per mission (Rc) and the maximum acceptable risk (Ec) enables to determine, from a qualitative point of view, the level of protection offered by the RPAS operation under interest; the level of protection might result as GOOD, ADEQUATE or NOT ADEQUATE following the rationale that the lower the risk as compared to a stringent threshold, the better the level of protection offered by the RPAS operation. To the end, there is the need to define two safety objectives: Ec1 and Ec2; Ec1 is the more stringent, Ec2 is the less stringent, i.e. the standard safety objective.

The compliance with the more stringent safety objective Ec1 (i.e. $Rc < Ec1$) , allows to consider the level of protection (offered by the RPAS operations under interest) towards third parties on ground as GOOD; the compliance with the standard safety objective Ec2 ($Ec1 \leq Rc < Ec2$) allows to consider the level of protection towards third parties on ground as ADEQUATE, while the un-compliance with Ec2 ($Ec2 \leq Rc$) leads to determine the level of protection as INADEQUATE.

RPAS operations under interests can be authorized when the level of protection offered is GOOD or ADEQUATE.

When the level of protection results as GOOD, standard limitation and condition (that should be defined in the frame of the SORA assessment. Ref figure 2) are appropriate to substantiate the safety of operations (limiting to protection of third party on ground), as better explained in §6.4.

When the level of protection results as ADEQUATE, specific limitations and conditions should integrate the standard ones, defined accordingly to the specific characteristics of RPAS operations (More details on what can constitute specific limitations and conditions are given in §6.4).

When the level of protection results as NOT ADEQUATE changes in the applied safety barriers should be defined, and this methodology positively iterated, before seeking for authorization.

The above additional safety barriers might be operational limitations more intrusive (as far as characteristics of the overflown areas , type of operations), different characteristics of the RPAS in term of different dimensions or safety features preventing possibility of explosion, for instance, or different RPAS reliability “performance”, so to reduce the likelihood of an impact on ground and, as a consequence, the level of the (mean) risk per mission.

A new evaluation of the level of protection following the introduction of the above additional safety barriers should be performed by iterating this methodology up to positive results, i.e. up to a level of protection resulting as GOOD or ADEQUATE.

The newly defined safety barriers should be considered as applicable and effective for the operations.

The flow diagram of the methodology sketched in this paragraph is drawn in figure 2 while §6.4 gives further details.

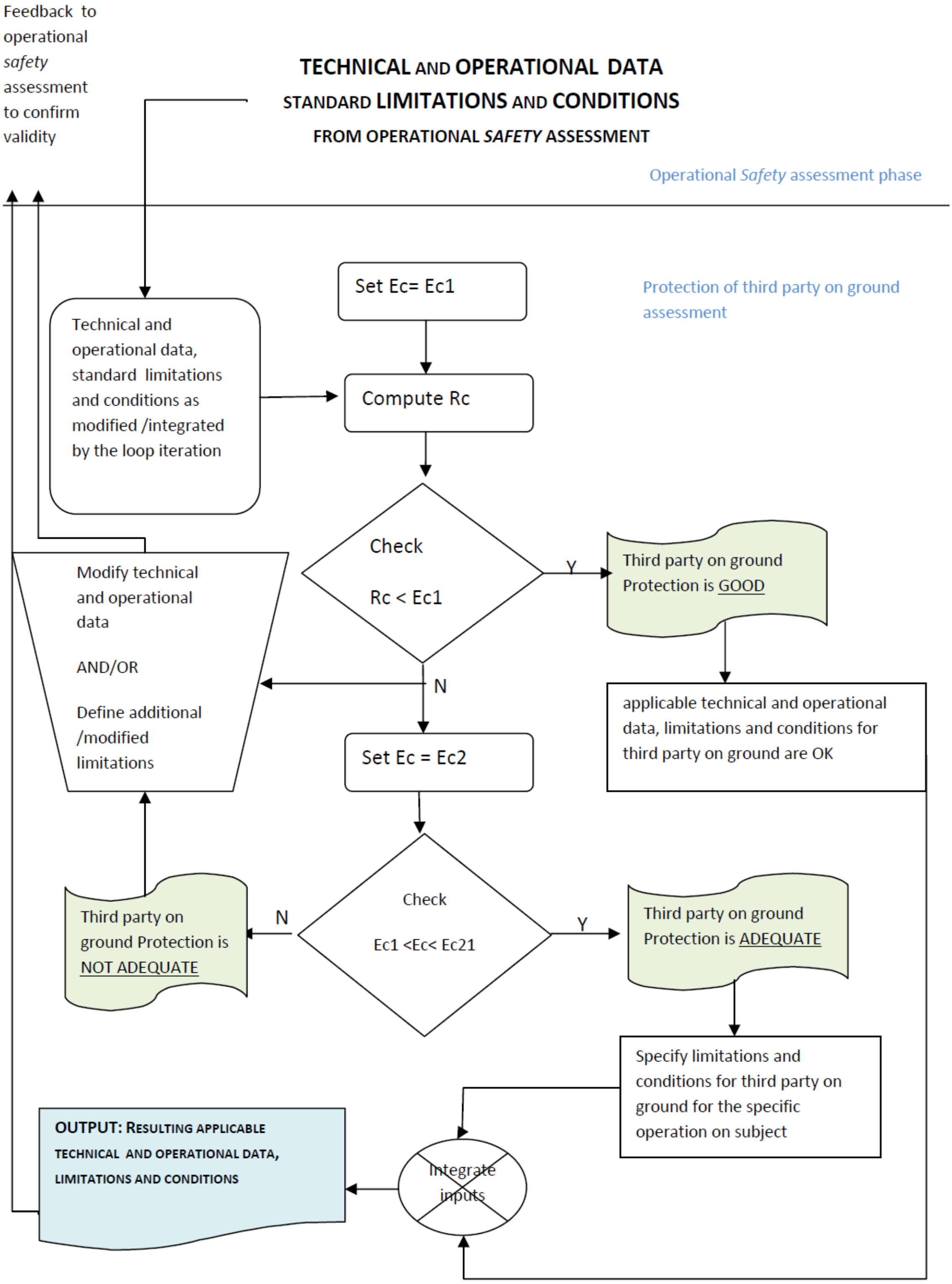

Figura 2 – Scaled safety objective approach flow diagram

6. Risk per mission (Rc) and Safety Objective (Ec)

6.1 Maximum acceptable risk per mission, acceptability thresholds and safety objective (Ec)

In this paper one "*casualty*" is defined as *"serious injury or worse, including human death"* [2].

The safety objective is represented by a value, Ec, defined as maximum mean value of casualties per mission; it is the maximum (as this value can be accepted while higher values cannot) mean value (i.e. expected value) of the casualties per mission, thus it can be understood as the **maximum risk acceptable per mission.**

The resolution of considering of interest the risk per mission more than the risk per hour has been taken as this is considered more directly linked to the public perception [3].

Briefly, the rationale behind this resolution, is that public perception of a highly critical event will not discriminate on how many hours operations have been running or how much time is spent during the mission (not even when compared to the standard segment) but it will perceive one operation as a whole, as one "risky window", irrespective of its time length. This assumption has been taken considering lectures in [3].

A deepening on the risk per mission vs risk per hour is given in §9

The validity of the methodology of this paper is not impaired by a possible different value of acceptability thresholds defined by each regulatory authority (e.g. NAAs).

6.2. Mean (i.e. expected) risk per mission (Rc)

The mean (expected) value of casualties per mission, i.e. the computed risk per mission (Rc), represents the average (mean value or expected value) of the number of casualties per mission; it shall not exceed the maximum acceptable number of casualties per mission (Ec):

(1) $R_c \leq E_c$

The mean (expected) value of casualties per mission (Rc) is determined as the probability that RPA crash on ground (uncontrolled landing/crash) times the number of people expected (mean value) inside RPA lethal area.

RPA lethal area is considered as the area in which any person inside would suffer a casualty following the impact.

The expected number of people (mean value) inside the lethal area is expressed simply as a function of the mean population density of the area which the lethal area stands on. By formula:

(2) $R_c = P_c \cdot N_c = P_c \cdot A_c \cdot D$

where:

Pc = probability of a crash (by any cause) during any mission.
Ac = RPA lethal area
D = mean population density inside lethal area
Nc = Ac*D= mean (expected) value of persons inside lethal area Ac

6.3 Criteria for determining the maximum acceptable risk per mission (Ec)

The maximum mean value of casualties per RPAS mission (Ec) is defined by the Regulatory Authority based on criteria linked to:

- equivalence of RPAS activities with different existing activities that can be considered as a valid reference;
- acceptance of the risk posed by operation by public perception [3]. As a matter of fact, generally, the level of risk that can be accepted by public perception decreases with the increase of unwanted consequences of the event and it depends more by those unwanted consequences than by the frequency itself of the event; on the other side, public perception tends to weight also the social benefit that a given operation can bring, while accepting the risk of the said operation.

In this paper, the principle of equivalence with standard manned civil aviation has been considered a valid criteria to define the acceptability risk threshold (Ec).

The above equivalence principle is read in the sense that the risk posed by RPAS operation towards third parties on ground should not exceed the risk posed by standard manned civil aviation operations towards involved people (mainly people on board).

As previously anticipated, two different safety objectives are needed, one more stringent (Ec1) and one standard safety objective (Ec2) so to be able to differentiate among three different qualitative levels of protection offered to third people on ground (GOOD, ADEQUATE or NOT ADEQUATE), depending on compliance with the more stringent objective, with the standard objective or with the un-compliance with both stringent and standard objectives.

6.3.1 Definition of the standard safety objective – Ec2

In order to define a valid value of the parameter Ec, the maximum (acceptable) value of casualties per mission, the estimation of the acceptable number of casualty per mission for the manned CS-23 is done.

For that segment (generally the general aviation segment) statistics are difficult to be interpreted, up to the level of impairing the validity of definition of Ec by looking at statistical data only; it is considered more valid to derive the estimation of the expected casualties per mission by the accident rate indicated as a valid reference value in the guidelines to the applicable manned certification specification (CS).

CS-23

- *Accident rate*[2] CAT (p): 1E-4/FH

Assumptions are needed, in order to derive the number of casualty per mission starting from the accident rate; those are:

- Mean mission time (T): 1 FH
- Mean people on board = Mean value of casualties in case of catastrophic event (Nc): 2

From the above:

- Probability of the crash (catastrophic event) per mission (Pc)

  Pc = (accident rate CAT)*(average mission time) = p*T = 1 FH x 1E-4 / FH = 1E-4

---

[2] Accident rate used by AMC23-1309()

- Acceptable risk per mission = mean value (expected) of *casualties* per mission (Ec):
  Ec = Pc * Nc = 2E-4

Thus, one estimation of the level of risk accepted for the manned general aviation segment, based on safety objective defined for the aircraft airworthiness is **2E-4** *casualty* per mission.

For the above, it is defined: **Ec2 = 2E-4**

6.3.2 Definition of the more stringent safety objective – Ec1

In order to define the more stringent safety objective it is considered to reference the statistics data coming from the international commercial civil aviation in term of number of casualties. To that end, it is considered as a source of data the ICAO *safety* report available at the date of issue of this paper. [4]

From the ICAO safety report, it is derived that the value of casualties per mission experienced during the period 2009-2013 is of the order of magnitude of 1E-5. It is considered that this value might be adequate for being the more stringent safety objective: Ec1=O[1E-5].

It is noted that, referencing [2] for space commercial operations (e.g. suborbital flights) the USA law require a safety objective of **Ec = 3E-5** *casualty* per mission (as maximum acceptable value) as far as protection of third party on ground is concerned. This USA safety objective is derived from the equivalence with USAF space operations. Moreover, in [2] it is substantiated how the 3E-5 objective, once properly translated in term of individual risk over a population of 100.000 citizens, results some order of magnitude less than individual risk for USA citizens due to non working activities.

For what above, it is deemed adequate and thus defined: **Ec1 = 3E-5**

6.4 Scaled safety objective approach

In order to augment the flexibility it is consider to retain the validity of both the safety objectives Ec2 and Ec1: Ec2 = 2E-4, in order to head to the equivalence with the "small" manned civil aviation, as well as Ec1 = 3E-5 in order to refer to the equivalence with the commercial International civil aviation and to a safety level accepted by the US society, somehow homogenous to the European society in term of expected (perceived) safety level (given the high communality of standards and harmonization of the two).

It means that we shall consider a “primary” safety objective the more stringent Ec1, and as a “support” safety objective the standard safety objective Ec2.

More precisely:

Ec1=3E-5 *casualty* per mission

Ec2=2E-4 *casualty* per mission

The more stringent (primary) safety objective is considered sufficient, when standard condition and limitations derived by the application of the SORA methodology are applied, to substantiate the minimization of the risk for the third party on ground for the missions to be authorized.

The standard (support) safety objective sets a sort of lower threshold that shall not be violated; such safety objective (Ec2), once accompanied by the standard conditions and limitations and with additional conditions and limitations to be defined specifically for the operations to be authorized, is considered adequate to minimize the risk to a level equivalent to the one reached by the compliance with Ec1.

At a first stage, the operator shall apply the SORA methodology and derive applicable conditions and limitations relevant to technical aspects, human factors aspects, environmental aspects and so on and shall check the compliance with the safety objective Ec1 (as far as -and limiting to- the protection of third party on ground is concerned!)

If Ec1 is not complied with, the compliance with Ec2 shall be checked together with the application of **additional and specific limitations and conditions**. Changes to the RPAS design features or to the operational characteristics are also possible if the compliance with Ec1 is mandated.

If Ec1<Rc<Ec2 examples of additional limitations and conditions to be authorized, specifically applicable to the RPAS operations, might be:

- Limitations on flight time (day/night/winter/summer…/total 1 hour and so on);
- Specific plans dedicated to the access of people on ground to be coordinated with the local administrations;
- Contingency plans with Policy, Fire Brigades, Coast Guard …;
- Emergency Recovery Procedure in predefined (and kept unpopulated) recovery areas;

- Sheltering;
- Etc.

The Scaled safety objective approach can be summarized as follows (ref to the flow diagram of figure 2):

1. Perform the SORA assessment and consider applicable the resulting (standard) condition and limitation as applicable to technical, human factor, environmental threats.
2. Set the safety target as the more stringent one: Ec=Ec1
3. Compute Rc relevant to RPAS operations to be authorized (assessed in the frame of the SORA assessment)
4. Make comparison between the safety objective and the risk: Rc≤Ec1 ?
5. If Rc≤Ec1, than conditions and limitation as per point 1 are appropriate. Else
6. Define changes in the RPAS or operational characteristics so to retrieve compliance with Ec1 (e.g. so to reduce the lethal area or the probability of crash on ground), or alternatively
7. Set the safety target as the standard one: Ec=Ec2
8. Make comparison between the safety objective and the risk: Rc≤Ec ?
    8.1 If Ec2>Rc>Ec1 then specify dedicated condition and limitation and be back to point 3.
    8.2 If Rc>Ec2 RPAS operation cannot be authorized as they are: changes in the RPAS or additional operational limitation shall be defined and considered applicable. Be back to point 1.

At the end, RPAS operations can be authorized in accordance with the present methodology when:

1) Rc≤Ec1 and standard limitations and conditions as applicable per the SORA assessment are applied, or
2) E1c<Rc≤Ec2 standard limitations and conditions as applicable per the SORA assessment + additional and specific limitations and conditions, are defined and applied.

7. Assumptions, variables and operational scenarios

7.1 Assumptions

The main assumptions on which the present methodology is based are listed below. If some of these assumption is disregarded or relaxed because it is judged not (completely or adequately) applicable to the specific problem under consideration, further justifications should be developed and provided.

(A1) *Uniform population density*. The area of operations must be subdivided in uniform population density zones. The uniformity of the population density is defined in terms of standard deviation of the population density distribution or in terms of local difference between the actual zone's population density and the mean population density in the area (see Para. 7.4).

(A2) *Buffer zone*. The buffer of a specific area of operations is defined as the region surrounding the area of operation into which the RPA could fall following a failure or malfunction that happen inside the nominal volume of operation over the area of operations.

As a general rule a buffer zone can be considered as related to a certain area of operations with a uniform population density if the RPA could fall there by escaping from that area of operations.

In order to simplify the analysis the buffer should have the same uniform population density of the related area of operations. Nevertheless if the buffer is too large (e.g. due to high altitude operations AGL), different uniform population density areas could be found within it. In this case either the ground path of the Instant Impact Point (IIP) is considered in the analysis (see the remark following the formula (25) at Para 9.2) or some hypothesis must be made on how to "spread" (in the risk formula) the time of flight Ti over the different areas of uniform population density in which the buffer has been subdivided. The details of this procedure should be agreed with the Authority.

For the aim of deriving the buffer only the **single failures or malfunctions** that could lead to an uncontrolled flight on ground of the RPA (or its pieces, debris, etc.) must be considered; that is, for each foreseen nominal trajectory to be flown over the nominal area of operations (with a certain uniform population density) the ground track of the RPA or its debris, including the impact point, must remain within the buffer in case of any **single** failure or malfunction that could led to an uncontrolled falling on ground.

A possible Emergency Recovery Procedure (ERP) that utilizes a Flight Termination System (FTS) or a preprogrammed trajectory to a specified recovery area i.a.w. JARUS CS-LURS Para. LURS.1412, LURS.561 along with the AMC to LURS.561 [6] can be taken into account. In that case the corresponding failures or malfunctions covered by the ERP could not be considered leading to an uncontrolled flight on ground and they could therefore be excluded by the failures and malfunctions to be considered for the buffer derivation.

Further details on the probabilistic criteria that could be used for deriving the buffer are explained in **Appendix B**.

(A3) *Uniform probability of fall*. The probability of an event that leads to an uncontrolled fall on ground is considered uniform.

Under this assumption the probability $Pc^{(j)}$ of an event that leads to an uncontrolled fall on ground (due either to technical design-related causes or to operation-related causes) during a certain phase of flight j (j=1,…,N) is the same for each phase of flight, i.e.: $Pc^{(1)}=Pc^{(2)}=\ldots=Pc^{(N)}=P$. In this case the probability of falling during a mission is Pc=N*P, because this event can happen during one and only one of the N phases of flight (mutually exclusive events). (Rif. Para. 9.2 and 9.3).

It is to be highlight that others scenarios can be envisaged, for which the probability of falling may be greater in certain phases of flight rather than in others. In this case the assumption (A3) is no longer valid and others assumptions shall be made for the probability distribution. *Eventually if the assumption (A3) cannot be taken as valid or otherwise sufficiently justified, then the risk model to be applied for the analysis shall be the model given by the relation (40)*.

(A4) *Constant Casualty Area*. Under this assumption the casualty areas Aci related to the phases of flight over the areas of operations Ai with uniform population density Di (i=1, … ,m) are all the same, i.e. the casualty area Ac is constant during the flight: Ac1=Ac2=…=Acm=Ac. A conservative approach consists in defining the constant casualty area as the greater casualty area among those associated to the various areas of operation overflown by the RPA: $A_C = max \ \{A_{C1}, \ \ldots, \ A_{Cm}\}$.

7.2 Operative variables

The main variables involved in the analysis are the following.

(V1) Uniform population densities (Di, i=1, …, m)

(V2) Times of flight over the areas of uniform population density (Ti, i=1, …,m).

(V3) Casualty area (Ac). In general it is a function of the RPA characteristics and of the specific phase of flight.

(V4) Probability Pci of falling into the area of uniform population density Di (i=1, …., m). It is different, in principle, form the probability Pc that is the probability of having an event that could lead to a fall on ground during the entire mission.

(V5) Maximum mean population density allowed for an area of operations within the present methodology (Dmax). For conducting the RPAS operations over an area with a mean population density above this value a (restricted) type certification could be required in principle.

(V6) Probability (f) of having an RPA explosion following an impact on ground. This probability could be evaluated by an engineering judgment based on a design assessment or by service experience of similar RPA.

For instance the following values could be assumed: f=0.1 for low probability of explosion, f=0.3 for low-medium probability, f=0.7 for medium-high probability and f=1 for high probability.

In any case the actual value of f to be used in the analysis must be agreed with the Authority.

(V7) Total mission time of flight (T).

7.3 Operative scenarios

Two possible main scenario are envisaged depending of the value of the probability Pc of having an event that could lead to an uncontrolled flight on ground: (S1) and (S2).

(S1) _ First scenario: Pc=1

In this scenario it is assumed that the RPAS reliability is totally unknown, as e.g. in case of COTS RPAS.

This scenario could be considered for authorizing the RPAS operations with a predefined (and not so large) casualty area, over predesigned experimental zones, characterized by a well defined and known population density distribution.

If the area is sparsely populated (i.e. with a non zero population density but less than Dmax) and if the casualty area is small enough, it would be possible to demonstrate a risk level Rc below the safety objective Ec even in the absence of any reliability data (i.e. assuming Pc=1) and with a limited experience of the Operator.

It is to be highlighted that if the assumption (A3) cannot be taken, i.e. when there are certain phases of flight more critical than others, then the relation (40) must be used (see what said at Para. 7.1 regarding the assumption (A3)) in conjunction with the following obvious constraint:

$$P_C = \sum_{j=1}^{N} P_C^{(j)} = 1$$

that brings to unity the probability of falling during the mission (N=number of different phases of flight in which the mission can be subdivided). Some precautionary hypothesis on the population densities D_{ij} present in the equation (40) could be taken into account.

The variables involved in the analysis are, in this case: V1, V2, V3, V6, V7.

(S2) Second scenario: Pc<1

In this scenario a specific value of the probability Pc must be justified for using it in the quantitative safety analysis aimed to demonstrate the safety objective Ec.

The variables involved in the analysis are, in this case: V1, V2, V3, V4, V6, V7.

The probability Pc can be estimated on the basis of:

i) The reliability of the design (considering both the systems and the structures) along with other considerations that would allow to pass from the (un)reliability of the design to the probability Pc including all other possible causes of fall as e.g. production aspects, operations, maintenance, etc.
ii) The data coming from service experience, adequately statistically treated in order to reach acceptable confidence levels.
iii) Other considerations based on engineering standards and literature data that could help in estimating the probability. In this case additional compensation and mitigation could be necessary.

The method ii) is deemed particularly suited for gradually opening the flight envelope in the context of the experimental activities or for operating in more congested area, as long as a greater reliability is demonstrated.

An example where an opening flight envelope is needed is a typical experimental situation in which there is little flight experience above non-populated areas. On the basis of this limited experience a probability Pc of uncontrolled crash on ground must be estimated for conducting the risk analysis, requested by the present methodology, for allowing the subsequent flights over populated areas.

In this case it is possible to utilize a Bayesian estimator for the probability Pc assuming a **uniform** *a priori* distribution over the interval [0,1]. The use of a uniform *a priori* distribution is justified by the fact that, reasonably, before the first experimental flights over the non-populated areas no relevant information on the reliability of the RPA was available, neither at design level nor at the service experience level on similar machines or on the same machine involved in similar operations. Therefore each value in the interval [0,1] could legitimately be assumed *as an a priori* probability of having an uncontrolled crash on ground. In other words in this case the probability Pc can be thought as a continuum random variable over the interval [0,1] with a uniform density $f(P_C) = \frac{1}{1-0} = 1$. The bayesian approach, starting from the *a priori* uniform distribution, provides an updating of this distribution of the probability Pc by using the information gathered in the previous experimental flight activity (over non-populated areas) in terms of the number of missions carried out and how many uncontrolled crash on ground occurred during these missions. The updated distribution is then used to derive an estimate of the probability Pc that can be used in the subsequent risk analysis.

Let us assume that in the first phase of experimental flight N missions have been carried out with n crash events. To model this scenario let us consider N Bernoulli's random variables X_i (i=1,…,N) *independent and identically distributed*. The i-th variable can only assume the value 0 or 1, when we *do not have* or, respectively, when we *have* an uncontrolled crash on ground during the i-th mission. The discrete probability distribution of these variables is therefore the following:

$$P(X_i = 1) = P_C$$

$$P(X_i = 0) = 1 - P_C$$

or

$$P(X_i = x) = (P_C)^x (1 - P_C)^{1-x}$$

where x=0,1.

Be $n = \sum_{i=1}^{N} x_i$ the number of the crash events occurred during the N missions carried out, where, again, $x_i \in \{0, 1\}$ is the value that the i-th Bernoulli random variable X_i can assume. Then the Bayesian estimator of the probability Pc of having an uncontrolled crash on ground during the next mission (and this Pc value can be used in the risk analysis) with a uniform *a priori* distribution, is given by [7]:

$$\hat{P}_C = \frac{n+1}{N+2}$$

For example, if N=10 missions have been carried out during which only one event has occurred (n=1) the mean (i.e. the maximum likelihood estimator) would be n/N=1/10=0.1, whereas the Bayesian estimator provides an higher updated estimate given by 2/12=1/6=0.17. It is clear that the Bayesian estimate is particularly suitable when the number N of the missions is not too large, because in this case we have an appreciable overestimation with respect the mean (with N=10 missions we move, in fact, from Pc=0.1 to Pc=0.17). On the other hand it is clear that as the number N of the missions increases the Bayesian estimator tends to the mean n/N.

The third scenario (S3) is considered apart.

(S3) Third scenario: D > Dmax

In this scenario the mean population density D is very high (> Dmax that is representative of a congested urban area), thus the only suitable approach for authorizing the RPAS operations is deemed a (restricted) TC.

In what follows, the present document takes into consideration only the two main scenarios (S1) and (S2) that are applicable only for a mean population density not greater than Dmax .

7.4 The level of uniformity of the area of operations

To establish a criterion for defining the population density uniformity of an area of operations or its part, the area is subdivided in M squared cells of side Lc.

Let

Aops = area of operations

Dc = mean population density in the area of operations

Lc = side of the cell, to be set based on geographical criteria lato (e.g. Lc = max dimension of the conurbation in the area of operations – e.g. Lc = 1 km or Lc = 100 m, in case a detailed map of the population density distribution is available)

Di = (mean) population density in the i-th cell of side Lc

The requirement of uniformity can be expressed by imposing to the population density Di of each cell in which the area of operations is subdivided, a maximum deviation (Δ) from the mean population density Dc:

(3) $D_C - \Delta \leq D_i \leq D_C + \Delta, \ (i = 1, \dots, M)$

where the deviation Δ can be selected by the Authority depending on the wanted level of uniformity (e.g. Δ = 1 inhabitant/km^2). This is a “local” criterion.

As an acceptable alternative the criterion of uniformity can be set in a more general way by defining a maximum acceptable value of the standard deviation of the population density distribution over the area of operations. This is a "global" criterion.

To this aim the area of operations is subdivided in M cells of side Lc with a mean population density Di. The population density Di is worked out by dividing the estimated number of inhabitants (or in general people inside) the i-th cell by the cell area $(Lc)^2$. This implies the availability the local population density distribution over the area of operations.

Having obtained the M population densities Di (i=1,…,M) along with the mean population density as $D_C = \frac{(D_1+\ldots+D_M)}{M}$, the standard deviation $\sigma(D)$ of the population density distribution is worked out by the following formula: $\sigma(D) = \sqrt{\frac{\sum_{i=1}^{M}(D_i-D_C)^2}{(M-1)}}$.

The more the standard deviation is low the more the area of operations can be considered uniform, therefore the requirement of uniformity can be set by requiring that the standard deviation be not greater than a certain value Δ (e.g. Δ = 1 inhabitant/km^2):

$$(4)\quad \sigma(D) = \sqrt{\frac{\sum_{i=1}^{M}(D_i-D_C)^2}{(M-1)}} < \Delta \,.$$

The criterion (3) is a local one because it requires that the density of *each* cell be not more distant from the mean than a certain value Δ; in this respect it is a less severe criterion with respect to the global criterion (4) that, conversely, requires that the standard deviation be not greater than the allowed deviation Δ. The standard deviation is a global measure. The criterion (4) is less severe than the (3) because there could be cells that exceed the allowed deviation (i.e. $|D_i - D_C| > \Delta$) even if the global standard deviation does not.

8. Casualty area (Ac)

The casualty area is an RPA characteristics and it is a function of its size, the flight path angle at impact and the quantity of fuel or other explosive material onboard. The casualty area Ac can be conservatively evaluated by using the following formulas [2] (see **Appendix A** for further details) in which two main contributions are added: an Inert Area (A_{inert}) due to direct impact of the RPA against people on ground and an Explosion Area (A_e) due to the blast overpressure coming from the explosion at impact:

(5) $A_c = A_{inert} + A_e = 7[2(r_p + \frac{L}{2})d + \pi(r_p + \frac{L}{2})^2] + \pi(K \cdot W^{\frac{1}{3}})^2$

where:

r_p = 1 ft

h_p = 6 ft

L = the max RPA size (e.g. max diameter)

γ = RPA flight path angle during the final phase of flight (or trajectory) just before impact

(6) $d = \frac{h_p}{tg\,\gamma}$

If the sole explosive material onboard is the gasoline or diesel fuel, we have:

(7) $W = 3.57 \cdot 10^{-4} \cdot V$

(8) $K = 18\, ft/lb^{\frac{1}{3}}$

where:

V = total volume of the RPA fuel tank(s) , in liters (lt)

W = fuel equivalent TNT mass in pounds (lb)

It is to be noticed that the relation (7) can be considered acceptable if the fuel is gasoline or kerosene; for other type of explosive materials the proper ratio of TNT-equivalent mass, to be used instead of equation (7), must be determined.

The K factor (8) takes account of the maximum blast overpressure of 3.5 psi allowed by the human eardrum without injuries.

The Explosion Area Ae gives in general a huge contribution to the total casualty area; nevertheless it is possible to alleviate this contribution by introducing in the Ae expression the multiplication coefficient f≤1 equal to the probability of having an explosion at the impact; the casualty area can then be expressed as follows:

(9) $$A_c = A_{inert} + A_e = 7[2(r_p + \tfrac{L}{2})\tfrac{h_p}{tg\,\gamma} + \pi(r_p + \tfrac{L}{2})^2] + \pi \cdot f \cdot (K \cdot W^{\frac{1}{3}})^2$$

By substituting the numerical values of the parameters (under the assumption that the unique explosive material is the gasoline or diesel fuel) the formula (9) becomes:

(10) $$A_c = 84\frac{(1+0.5L)}{tg\,\gamma} + 22(1+0.5L)^2 + 5.12 \cdot f \cdot (V)^{\frac{2}{3}}$$

where: $[A_C]=ft^2$, [L]=ft, [V]=lt , [f]=1.The experience on a specific RPAS shows that the possibility of having the projection of debris after an impact on ground cannot be excluded. In one case a four-meter diameter rotor wing RPA rolled over after an hard landing braking the main rotor blades and projecting parts of the blades at a distance of 20 meters away from the crash point. To conservatively take into account this fact a factor kd has been introduced in the formulas of the casualties area as better explained in **Appendix A**. The factor kd is defined as the ratio between the maximum distance from the impact point reached by the debris and the RPA maximum size. Following this approach the casualty area is corrected as follow (see **Appendix A** for the details):

(11) $$A'_C = A_c = A_{inert} + A_e, \qquad for \qquad r_f + r_p \leq \sqrt{7}(r_f + r_p)$$

(12) $$A'_C = A_C + \Delta = A_{inert} + A_e + \Delta, \qquad for \qquad \sqrt{7}(r_f + r_p + d) > k_d\, r_f + r_p > \sqrt{7}(r_f + r_p)$$

(13) $$A'_C = A_{debris} + A_e, \qquad for \qquad k_d\, r_f + r_p > \sqrt{7}(r_f + r_p + d)$$

where A_{debris} and Δ are given, respectively, by the (A10) and (A19) of Appendix A:

(A10) $$A_{debris} = \pi(k_d r_f + r_p)^2$$

(A19) $$\Delta = \tfrac{\pi}{2}[(k_d \cdot r_f + r_p)^2 - 7(r_p + r_f)^2] + (k_d \cdot r_f + r_p)^2 cos^{-1}\,[\tfrac{\sqrt{7}(r_p+r_f)}{k_d \cdot r_f + r_p}] +$$

$$- \sqrt{7}(r_p + r_f)\sqrt{(k_d \cdot r_f + r_p)^2 - 7(r_p + r_f)^2}$$

9. The safety objectives verification based on the population density

The methodology for performing the risk analysis in order verify the safety objectives is described hereafter in this Paragraph. Some practical examples are given and discussed at Paragraph 10.

The general criterion requires to work out the average number of casualty per mission (Rc) and then verifying that this figure is not greater than the safety objective Ec.

In the subsequent when we will refer to a "uniform area" we mean "an area in which the population density is uniform".

9.1 Case in which the area of operation is uniform

Let us consider the simpler case in which we have only a single uniform area of operations with population density D and the RPA is characterized by a constant casualty area Ac, then we have:

(14) $$R_C = P_C A_C D \leq E_C$$

By expressing the probability Pc as the sum of the probability $P_{failure}$ of having an uncontrolled fall on ground of the RPA during the time T due to technical causes (i.e. due to systems and structures failures or malfunctions) and the probability P_{ops} of having an uncontrolled fall on ground of the RPA during the time T due to operations (or, in any case, due to any other cause different from a technical cause), we can write:

(15) $$P_C = P_{failure} + P_{ops} = P_{failure}\left(1 + \frac{P_{ops}}{P_{failure}}\right) = k_f P_{failure}$$

(16) $$P_{failure} = p \cdot T$$

(17) $$k_f = 1 + \frac{P_{ops}}{P_{failure}}$$

where, from the (16), we have expressed the probability $P_{failure}$ as a function of the comprehensive systems and structures failure rate (p) of the RPAS and the total time of flight T, and where we have introduced, by the (17), the factor k_f as a function of the ratio $\frac{P_{ops}}{P_{failure}}$. The ratio $\frac{P_{ops}}{P_{failure}}$ can be estimated on the basis of the statistics and the service experience.

Thus, from the above expressions it is possible to express the probability Pc in terms of the comprehensive technical failure rate p related to an event that could lead to an uncontrolled fall on ground of the RPA, as:

(18) $P_C = k_f \cdot p \cdot T$

The general condition to be verified can then be written as follows:

(19) $R_C = k_f p T A_C D \leq E_C$

It is clear from the (14) or from the (19) that it would be possible to obtain a condition on one of the variables involved in the problem, once the others were known.

E.g. if the failure rate p is known along with the total time of flight T and the casualty area Ac, then it will be possible to work out the maximum allowed population density over which the RPA can fly, based on the following condition:

(20) $D \leq \frac{E_C}{P_C A_C} = \frac{E_C}{k_f p T A_C}$

9.2 Case in which the area of operations is not uniform

If the area of operations is not uniform, i.e. when its population density distribution is not uniform, it will be always possible to subdivide it in m areas Ai of uniform population density Di (i=1, …, m) derived i.a.w. the criteria of Para. 7.4.

Let Pci the probability of fall on ground (in an uncontrolled way) into the area Ai of density Di; such probability is in general different for each area Ai. In general even the casualty area Ac will be different for each phase of flight and, among a specific phase of flight, for each overflown area Ai, because the RPA geometry, the flight path angle and the quantity of fuel can vary during the flight.

The actual risk Rc can thus be worked out as the sum of the risks related to the RPA flight over the m areas Ai of uniform density Di, during the mission:

(21) $R_C = \sum_{i=1}^{m} P_{Ci} A_{Ci} D_i = P_{C1} A_{C1} D_1 + \ldots + P_{Cm} A_{Cm} D_m \leq E_C$

The inequality (21) must be used in conjunction with the following constraint:

(21a) $\sum_{i=1}^{m} P_{Ci} = P_C$

where Pc is the probability of crash on ground during the entire mission. The constraint (21a) is justified by the fact that the probability of a crash on ground during a mission (Pc) is the probability of an event that is the union of m events mutually exclusive given by the crash on ground over the different areas Ai, i.e.: Pc = Prob[(crash in area 1) OR (crash in area 2) OR … OR (crash in area m)]. During a mission the mutually exclusiveness come from the fact that the crash event can occur *in one and only one* area.

The probability Pci of falling into the area Ai of uniform density Di can be considered proportional[3] to the time of flight Ti over this area [2] and to the **probability Pc of falling on ground during the mission**, as

(22) $P_{Ci} = P_C \frac{T_i}{T} = P_C \cdot t_i$

where ti is the fraction of the total time of flight T over the area Ai:

(23) $t_i = \frac{T_i}{T},\ (i = 1, \ldots, m)$

Of course the following condition is true:

(24) $\sum_{i=1}^{m} T_i = T_1 + \ldots + T_m = T$

that is:

(25) $\sum_{i=1}^{m} t_i = t_1 + \ldots + t_m = 1$

<u>Remark.</u> It is to be highlighted at this point that, in principle, the time Ti is not simply the time of flight over over the area Ai but it should more properly be considered as the time during which the **instant impact point** (IIP) of the trajectory pass through the area Ai. The IIP is defined as the nominal point on ground to which the RPA would fall if an event that lead to an uncontrolled flight on ground occurred during the flight at a certain

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[3] The (22) can be interpreted as follow: Pci = Prob. ({RPA falls into Ai} AND {RPA falls during the mission}) = Prob (RPA falls during the mission) * Prob({RPA falls into Ai} | {RPA falls during the mission})

point of the trajectory. It is the clear that the IIP could lie on a certain area Ai following an event occurred outside the area Ai, not over it. It must also be taken into account that inevitably there will be a certain variation in the trace of the IIP o ground due to all the uncertainty involved in the problem and, in principle, such variation should be taken into account somehow (see also **Appendix B** as far as the buffer discussion is concerned). Even though for the sake of simplicity it is assumed that the time Ti is the time of flight over the area Ai, one should not forget the point for possible further refinement of the analysis (both in more conservative or less conservative sense).

By substituting the probability (22) into the risk expression (21) we get:

$$(26) \qquad R_C = P_C \sum_{i=1}^{m} A_{Ci} D_i t_i = P_C (A_{C1} D_1 t_1 + \ldots + A_{Cm} D_m t_m) \le E_C$$

Then, under the simplified assumption that all the casualty area Aci related to the overflown area Ai are the equal to Ac[4] , the equation (26) further simplifies itself becoming:

$$(27) \qquad R_C = P_C A_C \sum_{i=1}^{m} D_i t_i = P_C A_C (D_1 t_1 + \ldots + D_m t_m) \le E_C$$

from which the following condition is obtained:

$$(28) \qquad \sum_{i=1}^{m} D_i t_i = D_1 t_1 + \ldots + D_m t_m \le \frac{E_C}{P_C A_C}$$

The conditions (28), (25) and the other obvious conditions that the fractions t_i must non negative non negative, yield the following **simplified risk model**:

$$(29) \qquad \{ \; D_1 t_1 + \ldots + D_m t_m \le \frac{E_C}{(P_C A_C)} \quad t_1 + \ldots + t_m = 1 \quad t_i \ge 0 \quad (i = 1, \ldots, m)$$

The model (29) is valid under the assumption that the casualty area is constant during the mission.

Some variants of the model (29) follows.

In the first condition of (28) the total time of flight T during the mission does not explicitly appears, having expressed the probability P_C as a probability per mission and having used the fractions ti.

If there is the need to explicit the time T we can write the first of (28) as:

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[4] This is the assumption (A4), on the basis of which the casualty area Ac is the same for each uniform area overflown by the RPA. In order for this hypothesis to be conservative one must assume as casualty area Ac the greater casualty area of the RPA related to the different phases of flight.

(30) $$D_1T_1 + \ldots + D_mT_m \leq K_CT$$

where we have introduced the factor $K_C = \frac{E_C}{(P_CA_C)}$.

If the probability Pc can be expressed in terms of the technical failure rate p i.a.w. the (18) we get:

(31) $$K_CT = \frac{E_CT}{(P_CA_C)} = \frac{E_CT}{(k_fpTA_C)} = \frac{E_C}{(k_fpA_C)}$$

and the condition (30) would become:

(32) $$D_1T_1 + \ldots + D_mT \leq \frac{E_C}{(k_fpA_C)},$$

whereas if Pc=1 the condition (30) would become:

(33) $$D_1T_1 + \ldots + D_mT_m \leq K_CT = \frac{E_CT}{A_C}$$

or:

(34) $$D_1t_1 + \ldots + D_mt_m \leq \frac{E_C}{A_C} .$$

The set of conditions (29), along with the possible variants (30) – (34), can be used for verifying whether the safety objective Ec is respected by the specific mission planned: to this aim the trajectory will have to be designed such that each area Ai of uniform population density Di is overflown for a time not exceeding Ti = T*ti (i=1,…,m), where the fractions ti verify the conditions (29).

<u>Refining the model</u>

The risk model can be refined if the safety objective is not verified by using the simplified model (29).

A possible way for refining the model is to consider **N different phases of flight** during a single mission, instead of a single phase of flight coincidence with the mission as previously done.

Thus, let us consider N phases of flight j (j=1,…,N), e.g. (has applicable): takeoff, cruise, landing, hovering, other specific maneuvers, etc. During the j-th phase of flight the RPA flies over n_j areas A_{ij} of uniform population density D_{ij} (i=1,…,n_j). See Figure 3.

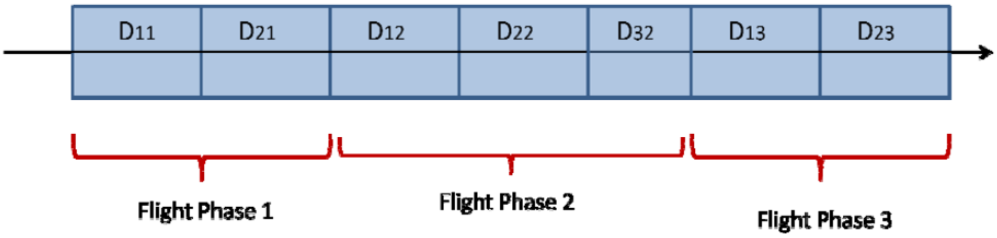


Figure 3 – Example of the mission subdivision in N distinct phases of flight characterized by different probabilities of having an event that lead to an uncontrolled fall on ground $Pc^{(j)}$ (j=1,…,N). During each phase of flight the RPA flies over different areas having uniform population density Dij (here N=3, $n_1=n_3=2$, $n_2=3$).

Let m the total number of uniform areas in which the overall area of operation has been subdivided, then:

(35) $$\sum_{j=1}^{N} n_j = n_1 + \ldots + n_N = m$$

Moreover, let:

A_{Cij} = Casualty area of the RPA when it flies over the area A_{ij} during the j-th phase of flight

$T^{(j)}$ = Total flight of time spent during the j-th phase of flight

T_{ij} = Time of flight spent over the area of density D_{ij} during the j-th phase of flight

with:

(36) $$\sum_{j=1}^{N} T^{(j)} = \sum_{j=1}^{N} \sum_{i=1}^{n_j} T_{ij} = T$$

$Pc^{(j)}$ = Probability of an event that could lead to an uncontrolled fall on ground during the j-th phase of flight

The probability $Pc^{(j)}$ depends on the specific characteristics of the j-th phase of flight and in principle is the same for all the areas overflown during the same or similar phase of flight (e.g. when the RPA flies over a certain number of uniform areas during the cruise, it could be assumed that the probability of having an event that could cause a fall on ground over each of the areas is the same)

One single phase of flight must therefore be thought as a phase of operations characterized by a well defined probability $Pc^{(j)}$ of having an event that could lead to an uncontrolled fall on ground.

The **probability** Pc_{ij} **of having a fall on ground into the i-th area** of uniform density Di during the j-th phase of flight can be found as the product of the probability of having an event that could lead to an uncontrolled fall on ground during the j-th phase of flight and the probability of flying over the i-th area of uniform density Di during the j-th phase of flight. Thus we get:

(37) $$P_{Cij} = P_C^{(j)} \cdot \frac{T_{ij}}{T^{(j)} = P_C^{(j)} \cdot t_{ij}}$$

(38) $$t_{ij} = \frac{T_{ij}}{T^{(j)}}$$

(39) $$\sum_{j=1}^{N} \sum_{i=1}^{n_j} t_{ij} = 1$$

Under the above positions the risk Rc can be expressed as the sum of the risks related to each phase of flight and to each uniform area overflown during each phase of flight:

(40) $$R_C = \sum_{j=1}^{N} \sum_{i=1}^{n_j} P_C^{(j)} A_{Cij} D_{ij} t_{ij} = \sum_{j=1}^{N} P_C^{(j)} \sum_{i=1}^{n_j} A_{Cij} D_{ij} t_{ij} \leq E_C$$

By taking properly into account the differences between each phase of flight and the conditions that exist during each phase of flight, the condition (30) for the risk can be used as a refinement of the model in order to obtain a more realistic (i.e. better evaluated) risk level to be compared with the safety objective.

It is also easy to see that by introducing the assumptions (A3) and (A4) into the (40) (i.e. by considering a uniform probability of having an uncontrolled fall on ground, equal for each phase of flight, and a constant casualty area) we obtain again the simplified model (29):

(41) $$P_C^{(1)} = P_C^{(2)} = \ldots = P_C^{(N)} = P$$

(42) $$P_C = P_C^{(1)} + P_C^{(2)} + \ldots + P_C^{(N)} = NP$$

(43) $$A_{Cij} = A_C \; (j = 1, \ldots, N; i = 1, \ldots, n_j)$$

Under these assumptions the general condition (40) reduces to the (27) with **P = Pc / N** that now plays the role that Pc played in the simplified model (we have in this case a risk reduction of N times – see the following remark)

Remark. It is to be noticed again that Pc is the probability of having an event that lead to a fall on ground during the entire mission (we mean the specific mission assumed for the analysis). The situation described above can be interpreted as if there were N distinct missions, for each of which the probability of having an event that lead to an uncontrolled flight on ground is equal to P. It is reasonable, then, that the probability P is less than Pc because in this context Pc is the probability of falling during *all* the N phases of flight. Furthermore, the equation (42) is justified by the fact that the event of falling during the entire mission can be seen as the union of N mutually exclusive events given by the falling on ground during the various phases of flight, each with the same probability P; thus we will have: Pc= Prob. [(RPA falls during phase # 1) OR (RPA falls during phase # 2) OR … OR (RPA falls during phase # N)] = N*P. The fact that these N events can be regarded as mutually exclusive comes from the fact that among one specific mission it is possible to have the falling on ground of the RPA just *in one and only one* phase of flight. Finally, it is obvious that the assumptions (41) and (43) have to be justified.

9.3 Considerations on the mission duration (mission time *vs* flight hour)

In this paragraph considerations are given on how an increase of the mission time T might affect the calculated risk per mission Rc and, after all, on how it might affect the compliance with the safety objective Ec. An increase of the mission time T might affect the probability of crash Pc during the mission. The consequences of expressing the safety objective in terms of casualty per mission rather than casualty per flight hours is analyzed as well.

I) Mission of different duration

We will analyze here the effect of increasing the total mission time T. Generally, if the (average) total mission time T changes, the probability of having a crash during the mission will change. In this sense the change of the value of T could imply a change of the ratios ti in the formula (29).

As explained at Para. 9.1, the probability Pc of having a crash during the mission could be thought as the sum of the probability of having a crash due to technical causes (even indirectly) and the probability of having a crash purely due to operational causes. The first probability (technical causes) is proportional to the technical failure rate p and to the total mission time T (see formula (16)); this might not be the case, in general, for the probability of crashing purely due to operational causes. Nevertheless when the number of crashes due to operational causes is known as a percentage over the total number of crashes (i.e. due to every causes), then the ratio between the probability of crash due to operations and the probability of crash due to technical systems is also known and then the probability Pc can be expressed as directly proportional to the total mission time T, as in the formula (18). This is the scenario depicted at Para. 7.3. (S2) i).

According to this scenario, let us assume, e.g., that the probability Pc for a certain type of mission having an average duration of 15 minutes (mission 1) has been estimated giving a value Pc1=0.01. Now let us suppose that the duration of this mission is increased up to 1 hour, actually getting to a different mission (mission 2), even though a mission of the "same type". In this case it could be reasonable to assume that the probability Pc is four time the original one: Pc2=4*Pc1=0.04. It is understood here that we are saying that in a sense the mission 2 is nothing more that the mission 4 repeated 4 time, which should be substantiated.

On the other hand, when the probability Pc is purely derived from service experience data, as in the depicted at Para. 7.3.(S2) ii), then it is not given from granted that the probability Pc is proportional to the mission time T. Moreover in this case it should be paid attention and carefully evaluated whether or not the original probability Pc could still be considered representative of the new mission with a different duration. Let us see an example. Let Pc= $Pc_{\_15}$ the Pc value derived from the service experience of missions having an average duration of 15 minutes. We would like to use this value for estimating the probability Pc= $Pc_{\_>15}$ of a crash in a missions whose average duration is greater than 15 minutes, without carrying out any further dedicated flight test. The question to be posed is then whether or not the assumption $Pc_{\_>15} = Pc_{\_15}$ could be considered acceptable. In general **the same value of Pc can be used for mission of different duration only if it is well justified, for example on the basis of an experimental activity carried out on the specific mission** to be considered, having an average duration representative of that assumed in the analysis.

At first, in the lack of justifications (as general information, analysis, experimental data, service experience, literature data, etc.) **the risk analysis should be worked out by assuming a probability Pc which is directly proportional to the total mission time T**, which is consistent with the hypothesis of uniform probability distribution over the overflown areas.

The scenario where Pc is not directly proportional to the total mission time T is consistent with a situation where the main contribution to the event “RPAS operation out of control” comes from systematic failures (including operational errors which repeat themselves systematically thus even not proportionally with the time duration) and that are not, in any case, uniformly distributed nor random events as those characterized by a constant failure rate (central region of the bathtub curve).

Hence it is important to pay attention to the fact that the value of Pc must be representative of “typical mission with a certain duration” and if this mission changes (e.g. if it lasts more) the value of the probability Pc shall be re-evaluated accordingly and possibly updated. The new Pc will be in general different from the original one.

In the specific case where the probability of crash can be considered uniformly distributed over the overflown areas it will be possible to use the simplified risk model (29). Let us see this case now in formula.

Let us consider a “mission (a)” having a duration Ta and a probability of crash Pca and a similar “mission (b)” of the same type of the mission (a) but with a greater mission time Tb=N*Ta (N>1). Let us assume then that both mission (a) and mission (b) overflow the same areas of uniformly population density Di.

Let’s consider the scenario of Probability of crash uniformly distributed over the overflown areas.

the risk model is $\sum_i D_i t_i = \frac{E_c}{P_C A_A}$ (Ec = constant) where, w.r.t formula (18), Pc is expressed generally as a function of the *failure rate* p and of the coefficient kf (that we assume as known) as: $P_C = k_f \cdot p \cdot T$. (ref. §7.3.(S2) i)).

For the mission (1) it is:

$$P_{C1} = k_f \cdot p \cdot T_1$$

$$\sum_i D_i t_i^{(1)} = \frac{E_c}{P_{C1} A_C}$$

from which $t_i^{(1)}$ are derived; while for the mission (2) it is:

$$T_2 = N \cdot T_1 \; (con \; N > 1)$$

$$P_{C2} = k_f \cdot p \cdot T_2 = k_f \cdot p \cdot N \cdot T_1 = N \cdot P_{C1}$$

$$\sum_i D_i t_i^{(2)} = \frac{E_c}{P_{C2} A_C} = \frac{E_c}{N P_{C1} A_C} < \frac{E_c}{P_{C1} A_C} = \sum_i D_i t_i^{(1)}$$

thus, $t_i^{(2)}$ relevant to the mission (2) are different from those of mission (1) , **and at least one shall be shorter considering, as said, the different values of Pc2 with respect to Pc1**. Generally speaking the time over densely populated areas shall be diminished accordingly, in order to still comply with Ec.

The above aims to point out that increasing the mission time T does not necessarily nor automatically lead to an easier compliance with the safety objective because either the probability of crash depends heavily (proportionally) from the mission duration (it increases when the mission duration increases) or, if the probability of crash is not proportional to the mission duration (e.g. when the systematic errors are the most significant causes of crash), it could not be uniformly distributed over the overflown area and, in this last case, the value of Pc for the longer mission should then be re-evaluated for each different phase of flight (over the different overflown areas). The updated level of risk of the new mission shall, in both cases, derived again and evaluated for compliance.

II) Safety objective as a function of flight hours

It can be easily pointed out that the model of risk does not change when the safety objective Ec is expressed as average number of casualty per flight hour and not per mission. It is obvious that the safety objective expressed as number of casualty per flight hour is consistently a number which is different from the number of casualty per mission; moreover, it is convenient to express the risk as a function of the *failure rate* p instead of the probability of crash per mission Pc, by the formula (18).

With e_C the safety objective per flight hour, i.e. the acceptable (average) number of casualties per flight hour and T the mission duration expressed in term of flight hours, then:

$$E_C = e_C T$$

$$\sum_i D_i t_i = \frac{E_c}{P_C A_C} = \frac{e_C T}{k_f p T A_C} = \frac{e_C}{k_f p A_C}$$

thus both the numerator and the denominator of the right side have been divided by T with no changes in the left side results.

The above reasonings cannot be applied when the probability of crash does not depend proportionally with the mission time T (as said above for cases where Pc is not uniformly distributed over the overflown areas or Pc is not driven mainly by random failure). It worths to be noted that, based on the fact that the safety objective Ec2 has been derived from the manned segment with equivalence with the general aviation, the number of casualty per flight hours ec and the number of casualty per mission Ec do not differ by any order of magnitude, being a mission a few units of hour, for such general aviation segment.

10. Examples

Example 1 – Small RPA (e.g. Microdrones)

Pc=1

From (14): Ec ≥ D Ac Pc

D < Ec/Ac

Ec = 1E-4

D_{max} = Ec/Ac maximum allowed value of the mean population density, function of the casualty area

Ac = 60 m^2 (casualty area without the contribution of the explosion area and without taking into account the debris projection, i.e.: f=0, kd=1)

D < 1.67 inhabitant/km^2

By introducing the time variable in term of the fraction of the total time of mission we can derive maximum time during which the RPA can fly over a uniform area with a greater population density, continuing to verify the safety objective Ec. As a matter of fact from (34), for: m=2, D0=0 inhabitant/km^2, D1 > 0 inhabitant/km^2, we get:

D1*(T1/T)+D0*(T0/T) = D1*T1/T < Ec/Ac

from which

T1_max / T = Ec / (Ac*D1)

Let us assume, e.g.: D1 = 5 inhabitant/km^2, then

T1/T = 1E-4/(6E-5 km^2 * 5 inhabitant/km^2) = 1/3 = 33% of the total mission time.

Eventually, this specific RPA, characterized by a casualty area Ac = 60 m^2 and by an unknown reliability, could in principle operate without any time limitation over an area with a uniform population density of 1.67 inhabitant/km^2, or it could carry out operations over an area with a uniform population density of 5 inhabitant/km^2 for 1/3 of the total mission time and for the rest of the time over areas with zero uniform population density, irrespective to the mission duration; this because the probability Pc=1 is the probability of falling per mission and the objective Ec is expressed per mission as well; it is clear, then, that the probability of falling into the area with a non zero population density it will be equal to the fraction of the time during which the RPA flies over this area (1/3 in this case) **under the hypothesis that the assumption (A3) is valid**. As a matter of fact if the assumption (A3) were not valid a non uniform probability distribution should have been taken into account into the model and the equation (40) for the risk should have been applied, with j=2 and with two different probabilities of falling into the two areas, not necessarily proportional to the corresponding times of flight.

Example 2 – Medium RPA (e.g. Sistemi Dinamici RUAS-HERO – 150 kg MTOM)

Data and assumptions:
$\gamma = 45°$
L = 4 m = 13 ft
M_{fuel} = 37.5 kg = 82.7 lb (50 l)

V=50 lt (fuel tank capacity)

f=1
kd=5

$$A_C = A'_c = A'_c(L,\ \gamma, f) == 84\frac{(1+0.5L\ )}{tg\ \gamma} + 22(1+0.5L\ )^2 + 5.12 \cdot f \cdot (V\ )^{\frac{2}{3}} \quad + (2.5L+1)^2\{1.57 + cos^{-1}\ [\frac{2.65(0.5L+1)}{2.5L+1}]\ \} +$$

$$- 2.65(0.5L+1)[4.16(0.5L+1) + \sqrt{(2.5L+1)^2 - 7(0.5L+1)^2]}$$

(0.5L+1)=0.5*13+1=7.5 ft

(2.5L+1)=2.5*13+1=33.5 ft

tg γ=tg(45°)=1

arcos(2.65*7.5/33.5) = 53.6°= 0.9357 rad

Ac= 84*7.5 + 22*7.5^2 + 5.12*(50)^(2/3) + 33.5^2*[1.57 + 0.9357] -2.65*7.5*[4.16*7.5+√(33.5^2-7*7.5^2)] =

= 630 + 1237.5 + 69.5 + 2812 – 1156.54 =

= 630 + 1237.5 + 69.5 (explosion) + 1655.5 (debris) =

= 3592.5 ft^2 = 333.75 m^2 = **3.3375E-4 km^2**

Let us assume now a conservative flight path angle of 3°; in this case the corresponding contribution to the casualty area would be

$84\frac{(1+0.5L\ )}{tg\ \gamma}$ =84*7.5/.0524=1459.7 ft^2

instead of the previous value of 630 ft^2 corresponding to 45°, with and amplification factor of about 2; therefore the percentage variation of the casualty area moving from a flight path angle of 45° to a an angle of 3° is equal to 23% and then it cannot be neglected:

Ac(γ=45°)=3592.5 ft^2

Ac(γ=3°)=1459.7+1237.5+69.5+1655.5=4422.2 ft^2

Delta Ac% = 100*(4422 – 3593)/3593 = 23 %

Let us consider now an operative scenario where there is a single area of operations with a uniform population density D, to be determined in order to match the objective.

Let:

Ac = Ac(γ=45°)

Ec1=3E-5

Ec2=2E-4
Rc1=Ac*D<Ec1 → D<Ec1/Ac=3E-5/3.3375E-4 =9E-2 inhabitant/km^2 = about 0 inhabitant /km^2
Rc2=Ac*D<Ec2 →D<Ec2/Ac=2E-4/3.3375E-4 =0.6 inhabitant/km^2.

Based on the less severe safety objective Ec2=2E-4 the RPA could then operate over a uniform area with a population density not greater than 0.6 inhabitant/km^2 irrespective of the total mission time. Nevertheless this population density value is quite low and it could be not adequate for the aims of the mission, when e.g. it were requested to operate over sparsely populated areas of 5 to 10 inhabitants per km^2.

From the above it is then clear the need of an approach based on a repartition of the time of flight over areas with different population densities.

Thus, let us consider, e.g., two areas of uniform population density D1 and D2 respectively, along with an unpopulated area with zero population density D0 (e.g. over the sea):
D0 = 0 inhabitant/km^2
D1 = 10 inhabitant/km^2
D2 = 5 inhabitant/km^2

Let us assume the following safety objective: Ec=Ec2=2E-4
Let us assume a total time of flight (the mission duration) T = 1 h and try to work out the overflown time percentages t1=T1/T, t2=T2/T, t0=T0/T such that:
D1*t1 + D2*t2≤Ec2/Pc*Ac=Kc
t0+t1+t2=1
ti≥0 (i=0,1,2)

It must be noticed that if an area with zero population density is considered it will be always possible, in principle, to work out the fractions t1 and t2 such that the safety objective is verified, by imposing that the RPA operates over the area with zero population density for a percentage of time t0=1-(t1+t2) and for the rest of the time over the remaining area with non zero density. Of course, the more the percentage of time do be spent over zero density areas is, the less the operative advantage of flying over non zero density areas will be.

In what follow the situation in which Pc< 1 shall be considered.

The objective is: $Ec2=2E-4$

The casualty area is: $Ac=3.3375E-4\ km^2$

Pc=0.1 (this value for Pc is conservatively estimated by considering 1 crash event taken from the RPA RUAS-HERO service experience of 15 FH of operations, with an average mission duration of 15 minutes).

$Kc=Ec/(Pc*Ac)=(2E-4)/(0.1*3.3375E-4)=2/(0.33375)=6$

The conditions to be applied, from the simplified risk model (29), are the following:

(1) $10*t1+5*t2\leq 6 \rightarrow 2*t1+t2\leq 6/5=1.2$
(2) $t0+t1+t2=1$
(3) $t0\geq 0,\ t1\geq 0,\ t0\geq 0$

By substituting t2, from the (2), into the (1) we have

$t2=1-t0-t1$

$2*t1+1-t0-t1=t1+1-t0\leq 1.2 \rightarrow t1\leq t0+0.2$

Thus we have:

$t1\leq t0+0.2$

$t2=1-t0-t1$

$t0\geq 0,\ t1\geq 0,\ t0\geq 0$

Let us choice e.g. **t0=0.4**, then we have $t1\leq t0+0.2=0.4+0.2=0.6$. Now let us choice **t1=0.2**, from which we finally have the value of t2 by complementing to unity with respect to t0 and t1: **t2=**1-0.4-0.2**=0.4**.

Check (Ref. (1) e (2)):

$t0+t1+t2=0.4+0.2+0.4=1 \rightarrow$ OK

$2*t1+t2=2*0.2+0.4=0.8<1.2 \rightarrow$OK

Eventually, based on the above analysis, a possible solution that lead to the verification of the safety objective Ec2=2E-4, is the following: the RPA can fly

- **at least 40%** of the total mission time over an area of density D0=0 inhabitant/km^2 (e.g. over the sea),
- **no more than 20%** of the total mission time over an area of density D1=10 inhabitant/km^2, and
- **no more than 40%** of the total mission time over an area of density D2=5 inhabitant/km^2.

Assuming T=1h=3600 s we would have the following times of flight:

- Over an area with density D0=0 inhabitant/km^2:	**T0**=3600*0.4=1440 s **= 24 min** (*)
- Over an area with density D1=10 inhabitant/km^2:	**T1**=3600*0.2 = 720 s **= 12 min**
- Over an area with density D2=5 inhabitant/km^2:	**T2**=3600*0.4 = 1440 s **= 24 min**

(*) Remark. Because the time of flight over an area of zero population density (obviously) does not contribute to the actual risk Rc of the mission (indeed the corresponding term in the risk formula vanishes, being proportional to the density) it is possible to fly over a zero density area for a time greater than the time T0 coming by (or, better, assumed in) the analysis; thus the time T0 (or the percentage t0) related to the area with zero population density must be considered as the minimum time to be flown over this area (from here phase "at least" in the above examples)

Let us consider now the safety objective that is more severe, i.e.:

Ec=Ec1=3E-5

Pc=0.1

Ac=3.3375E-4 km^2

Kc=Ec/(Pc*Ac)=3E-5/(0.1*3.3375E-4)=3/3.3375=0.9

10*t1+5*t2≤0.9 → **2*t1+t2≤**0.9/5=**0.18** (risk inequality)

t2=1-t0-t1

t0≥0, t1≥0, t0≥0

Substituting t2=1-t0-t1 into the above risk inequality we get:

2*t1+1-t0-t1=t1+1-t0≤0.18 → t1≤t0-0.82

Then form t1≥0 we have:

0≤t1≤t0-0.82 → t0-0.82≥0 → t0≥0.82

Let us thus choice **t0=0.9** from which t1≤t0-0.82=0.08. Now let us choice **t1=0.03** from which, by complementing to unity: **t2**=1-t0-t1=1-0.9-0.03=**0.07**.

Check:

2*t1+t2=2*0.03+0.07=0.13<0.18 → OK

Thus, a possible solution that respects the safety objective Ec1=3E-5 is flying for at least **90%** of the total mission time over a zone with a population density **D0=0 inhabitant /km^2** (e.g. over the sea), for no more than **3%** of the total mission time over the zone with a population density **D1=10 inhabitant/km^2** and for no more than **7 %** of the total mission time over the zone with population density **D2=5 inhabitant/km^2**.

Ex. 3 – Pc not uniformly distributed during the mission

Now, let's take into account a case where the probability of crash on ground is derived from service experience data, processed by appropriate statistical considerations (ref. §7.3.(S2) ii)).

This might or might not represent a case where direct proportionality with time of Pc is justified.

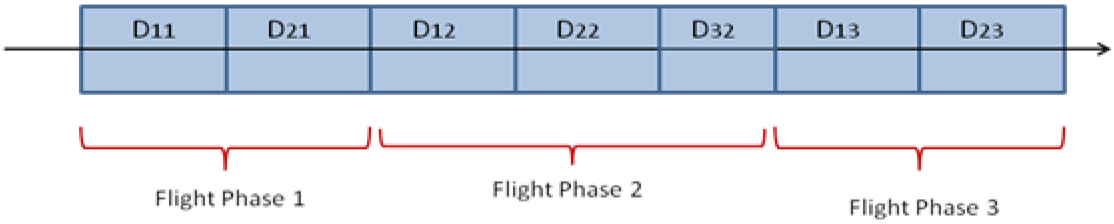
As expressed at the beginning of Para. 9.3, when there is no additional information on the dependency of Pc from the mission duration, directional proportionality with time should be considered a reasonable assumption and considerations in Para. 9.3 for the case where Pc is proportional with time do apply.

If the value of Pc is not directly proportional with time during the entire mission (i.e. uniformly distributed) the formula (29) should not be used.

In such a case the formula (21) might fit well the risk model, where the risk of the mission is the result of the sum of the risks for each phase of flight, where the dependency with time is not explicit and the risk is given, mostly, with respect to the population density of each overflown areas.

Formula (21) is:

$$R_C = \sum_{i=1}^{m} P_{Ci} A_{Ci} D_i = P_{C1} A_{C1} D_1 + \ldots + P_{Cm} A_{Cm} D_m \leq E_C$$



According to the above Fig. 3, the densities Di in the formula (21), with m=7, are: D1=D11, D2=D21, D3=D12, D4=D22, D5=D32, D6=D13, D7=D23.

In the formula (21) P_{Ci} might have different values in case there are phases of flight considered more risky than others or parts of the same phase of flight, over different areas, more risky than others, and the values of Di factors should be considered according to the overflown areas during such phases.

In some cases, the values of Aci can also be different; for instance if a parachute is used as an FTS and the parachute might be less effective for some flight phases, a value of the casualty area different from the one where the FTS is well proven as effective might be deemed as necessary (Ref. to Para “Considerations on the use of the parachute as FTS”).

We consider that the following operational characteristics might be sufficiently generic to be of interest:

Flight Phase 1 = Take Off

Flight Phase 2 = Cruise

Flight Phase 3 = Landing

D11=D21 = $D_{T.O.}$ (Take Off)

D12=D22=D32 = D_{Cr} (Cruise)

D13=D23 = D_L (Landing)

Let's consider that the Pc, proven by service experience and processed by statistics consideration, is Pc =0.1 crash on ground per mission.

For this example, we consider of interest a case where takeoff and landing are phases more risky than the cruise phase.

This might be justified by different rationales; for instance, where takeoff and landing are fully automated with a behavior less proven than during the other flight phases; or as well where pilot workload is increased to a level of slightly impairing his/her efficiency due to flight characteristics during such phases, or when an human error is considered more probable or more critic.

As far as the cruise phase is concerned, the probability of crash during that phase might be considered proportional with time; this might account for cases where specific information on such phase is not available and the proportionality with time is a reasonable assumption. This information is not used for this example but a the end of this paragraph.

Let's call the probability of crash during take of $P_{T.O.}$, the probability of crash during cruise P_{Cr} and the probability of crash during landing P_L.

Condition (21a) thus reads

$$P_{T.O.} + P_{Cr} + P_L = P_C$$

The increase of the risk during takeoff and landing can be apportioned based on experienced operational judgment.

Let's consider $P_{T.O.}$ = P_L = 40% of Pc and consequently Pcr = 20% of Pc. Thus: $P_{T.O.} = P_L = 0.4P_C$, $P_{Cr} = 0.2P_C$.

For the sake of generalities, let's consider in this example that the casualty area Ac is unchanged in those three flight phases.

Formula (21) then reads:

$$R_C = P_{T.O.} A_C D_{T.O.} + P_{Cr} A_C D_{Cr} + P_L A_C D_L \leq E_C$$

$$R_C = P_C \cdot A_C (0.4 \cdot D_{T.O.} + 0.2 \cdot D_{Cr} + 0.4 \cdot D_L)$$

As for the example of Microdrones, let's consider:

$Ac = 60\ m^2$ = 6E-5 km^2, and

$D_{T.O.}$ = D_L = 2 ab/km^2, while

D_{Cr} = 10 ab/km^2

Then, finally, the result is

Rc=(0.1)(6E-5)(0.4*2+0.2*10+0.4*2)= (6E-6)(3.6) = 2.1E-5 < Ec1=3E-5 → OK

The compliance with the safety objectives can be easily derived and relevant consequences i.a.w. the present paper taken.

When the mission duration is increased, specific consideration should be done in order to justify how the value of Pc has to be changed along with the values of $P_{T.O.}$, $P_{L,}$ P_{Cr}, due to the condition (21a).

In such a case the direct proportionality with time of the probability P_{Cr} assumed for this example could be used.

Appendix A

RPA casualty area determination

For what follows we will mostly refer to [2]. It is assumed here that there is the possibility to have both an inert impact area (A_{inert}) and a casualty area due to a possible explosion (Ae) in case, e.g., the RPA carries fuel onboard or other potentially explosive materials. For simplicity it is assumed here that the only potentially explosive material onboard the RPA is the fuel, i.e. gasoline or kerosene.

The scenario considered here foresees that the RPA follows a **straight trajectory** toward the ground, at the impact point I, inclined by a flight path angle **γ** (Fig. A-1).

The inert area A_{inert} is worked out as follows. First a basic area (Ab) is derived, which account for the direct impact of the RPA to a person standing inside the area. A person is simulated here by a cylinder with a radius r_p=1 ft and an height h_p=6 ft (Fig. A-1):

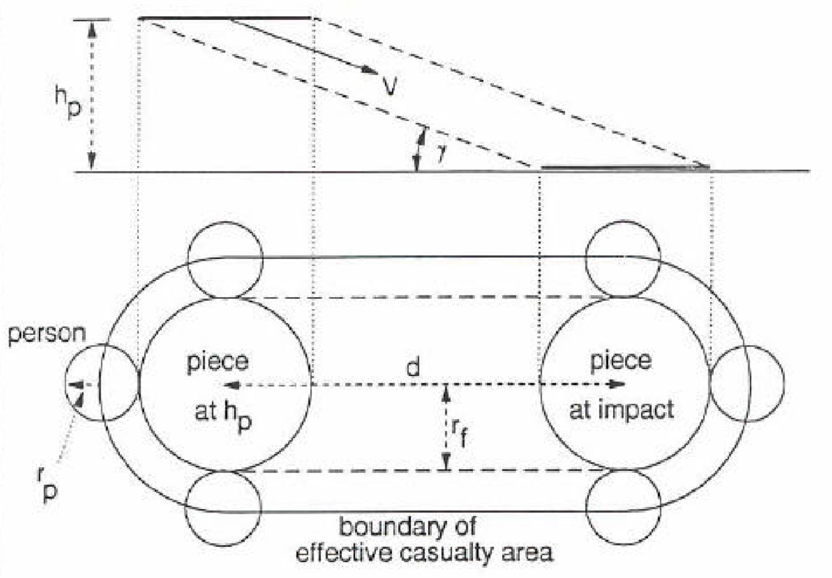


Figure A-1 – Basic area (A_b) derivation

From Figure A-1 it is possible to derive the basic area as follows:

(A1) $A_b = 2(r_p + r_f)d + \pi(r_p + r_f)^2$

(A2) $d = \frac{h_p}{tg\,\gamma}$

where r_f= L/2 and L is the **maximum size of the RPA**.

In order to account for a possible rebound and/or skidding of the RPA on the ground after the impact at the point I, the basic area A_b is conservatively increased by a factor 7, as recommended in [2]:

(A3) $A_{inert} = 7A_b = 7[2(r_p + r_f)d + \pi(r_p + r_f)^2]$

In order to get the casualty area, the inert area is conservatively simply summed up with the explosion area (Ae), without any superposition, even if the point of explosion could be expected to be centered inside the inert area. In this way the inert and casualty areas are assumed to be disjoint in order to maximize the casualty area.

A circular explosion area is considered, whose radius (R_e) can be worked out by the following formula:

(A4) $R_e = K \cdot W^{\frac{1}{3}}$

(A5) $W = 10 \cdot M_{fuel\ vap} = 0.3 \cdot M_{fuel\ vap}$

(A6) $K = 18\, ft/lb^{\frac{1}{3}}$

Where $= 0.03$ is the **reaction efficiency**, representative of the fraction of reaction energy available for the propagation of the pressure wave. $M_{fuel\ vap}$ is the fuel mass in the vapour phase expressed in pounds (lb) corresponding to the **upper ignition limit** of the fuel expressed as the % volume of the fuel vapour with respect the total volume V of the tanks(s) including the tank volume occupied by the liquid fuel.

As far as gasoline or kerosene are concerned the upper ignition point corresponds to a concentration of 6.5% in volume; it is therefore possible to obtain the vapor fuel mass $M_{fuel\ vap}$ to be considered in the formula (A5) as $M_{fuel\ vap} = 0.065 \cdot V \cdot \rho_{fuel\ vap}$ being $\rho_{fuel\ vap}$ the vapour fuel density.

From the literature it is then possible to obtain that, in ambient temperature and humidity conditions, the gasoline vapor density is 3.5 times the density of the air, whereas the kerosene vapour density is 7 times the density of the air; therefore, taking conservatively into account the density of the kerosene vapor, that is the higher, one gets: $\rho_{fuel\ vap} = 7\rho_a$ where $\rho_a = 1.184\ kg/m^3$ is the density of the air in standard ambient conditions (i.e. 25°C, 1 atm). Eventually we obtain: $M_{fuel\ vap}[kg] = (0.065)7(1.184)V = 0.54 \cdot V\ [m^3]$ or, by expressing the fuel mass in pounds and the volume V in liters (0.54 kg=1.19 lb, 1 m3=1000 lt) we will have: $M_{fuel\ vap}[lb] = 0.00119 \cdot V\ [lt]$. Thus the formula (A5) becomes (again, as far as gasoline or kerosene are concerned):

(A5’) $W[lb] = 3.57 \cdot 10^{-4} \cdot V\,[lt]$

The mass W in the formula (A5) or (A5’) is the fuel TNT-equivalent mass and it can be used for kerosene and (conservatively) for gasoline. For other type of potentially explosive materials (gas, liquid or solid) the appropriate ratio for obtaining the TNT-equivalent mass in the formula (A5) must be determined.

The factor K (known as the “K-factor”) in the formula (A6) takes into account the maximum level of the blast overpressure bearable by the 99% of the exposed unprotected population without any injuries (typically at the eardrum). The K-factor corresponds to an overpressure of 3.5 psi. It should also be taken into account that an overpressure of 0.5 psi is able to yield to window breakage with potential injuries of the building occupants. Nevertheless the present document does not apply to RPA flights over highly populated zones (ref. to Para. 7.3, scenario (S3)) that are characteristic of an urban environment, therefore it is possible to assume for the present analysis an overpressure of 3.5 psi as the minimum blast overpressure capable to produce injuries to unprotected people outdoor.

The total casualty area will be the sum of the inert area, given by the formula (A3), and the explosion area, whose radius is expressed by the formula (A4), times a factor f≤1 which represents the probability of having an explosion at impact:

(A7) $$A_c = A_{inert} + A_e = 7[2(r_p + r_f)\frac{h_p}{tg\,\gamma} + \pi(r_p + r_f)^2] + \pi \cdot f \cdot (K \cdot W^{\frac{1}{3}})^2$$

or, taking into account the formulas (A5’) and (A6) :

(A8) $$A_c[ft^2] = 84\frac{(1+0.5L\ [ft])}{tg\ \gamma} + 22(1+0.5L\ [ft])^2 + 5.12 \cdot f \cdot (V\ [lt])^{\frac{2}{3}}$$

From the point of view of the *form* of the casualty area the coefficient 7 can be thought as distributed between the radius $r_p + r_f$ of the semi-circumference of the basic area and its longest side (d) such that the equation (A3) is verified (see Figure A-2):

(A9) $$A_{inert} = 7[2(r_p + r_f)d + \pi(r_p + r_f)^2] = 2[\sqrt{7}\,(r_p + r_f)]\sqrt{7}\,d + \pi[\sqrt{7}\,(r_p + r_f)]^2$$

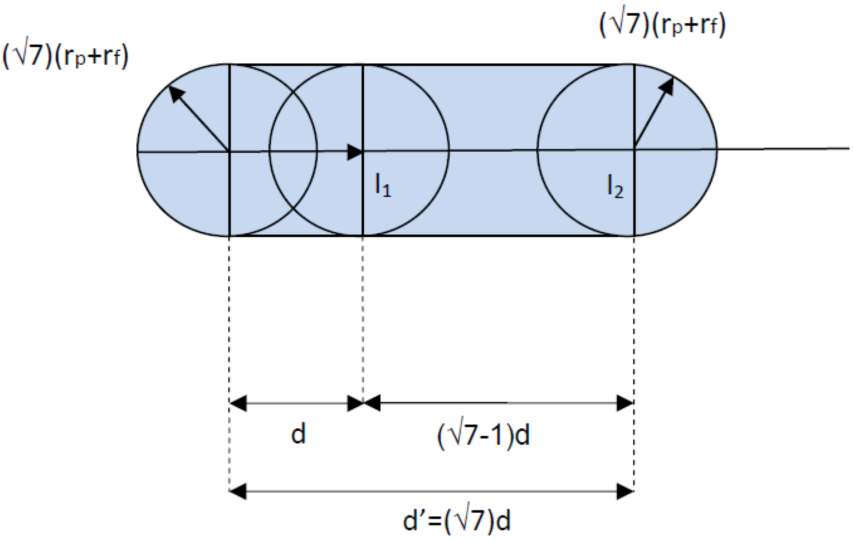


Figure A-2 – Possible form of the casualty area considering the repartition of the factor 7 between the radius of the semi-circumference at the extremes and the longest side of the basic area. I_1 = First impact point. I_2 = Final arrival point after rebound and skidding of the RPA.

If there is the possibility for parts or debris to be projected away from the point of impact (we could have this possibility for a rotary wing RPA that loose the blades after an impact) the casualty area is corrected for taking into account this aspect. Let A'_C be the casualty area corrected for taking into account the effect of debris.

The service experience gathered up to now report an event of a crash where a 150 kg-MTOM RPA having a maximum size L of about 4 m, has projected parts of the main rotor blades to a distance of about 20 m away from the impact point. Thus, based on this service experience we can say that, starting from the impact point, the debris were projected up to a distance equal to 5 times the maximum size L of the RPA, which defines an empirical *debris factor* k_d=20/4=5 to be multiplied to the characteristic size L of the RPA in order to obtain an estimation of the maximum distance from the impact point reachable by the debris.

With reference to Figure A-3 it could be cautionary assumed[5] that the breakage and the loosing of the parts happen at the farthest point got by that the RPA after the possible rebound and skidding on the ground (point I_2 of Figure A-2); starting from this point the debris reach a distance of $r'_f = k_d \cdot r_f$ and therefore they are potentially dangerous for any individual (of radius r_p) who stays at a distance less than or equal to $r'_f + r_p$ from the point I_2 (the breakage point).

Now, let:

(A10) $A_{debris} = \pi(k_d r_f + r_p)^2$

The circular area of radius $r'_f + r_p$ equal to the lethal distance due to the debris projection, centered at point I_2. We will call A_{debris} the *debris area*.

For the aim of work out the correction of the casualty area due to the debris projection, three cases are hereafter considered:

a) The circular region of area A_{debris} *is included* inside the inert region of area A_{inert}; such condition can be expressed by the formula:

(A11) $k_d r_f + r_p \leq \sqrt{7}(r_f + r_p)$

---

[5] See note 6.

In such case it is not necessary to correct the casualty area A_C to take into account the debris projection because they will fall inside the inert area, which is already taken into account by the inflation factor 7 of the inert area in the formula (A3).

b) The circular region of area A_{debris} *intersects* the inert region of area A_{inert} but it is not completely included in. This condition can be expressed by the following relation:

(A12) $\sqrt{7}(r_f + r_p + d) > k_d r_f + r_p > \sqrt{7}(r_f + r_p)$

In this case the casualty area A_C must be corrected by a term Δ as further explained.

c) The circular region of area A_{debris} *completely includes* the inert region of area A_{inert} ; this condition is expressed by the following relation:

(A13) $k_d r_f + r_p > \sqrt{7}(r_f + r_p + d)$

In this case the casualty area can be expressed as the sum of the circular debris area and the explosion area that conservatively is added to the debris area irrespective whether or not it is actually included in.

Casualty Area in the Case a)

In this case the condition (A11) applies, thus the casualty area keep being expressed by the formula (A7) or (A8):

(A14) $A'_C = A_c = A_{inert} + A_e$.

Casualty Area in the Case b)

In this case the condition (A12) applies and we have an additional term Δ worked out as the difference between the debris area (A10) of the circle of radius $r'_f + r_p$ centered in I_2 and the area of the inert region (inflated by the factor 7, as described in Figure A-2) included inside the said circle[6].

Thus, let (see Figure A-3):

C = Semicircular crown area (EBCF) centered at point I_2, with external radius $r_f' + r_p$ and internal radius $\sqrt{7}(r_f + r_p)$

S = Area of the circular sector (I_2AB) = Area of the circular sector (I_2CD)

T = Area of the triangle (I_2AE) = Area of the triangle (I_2FD)

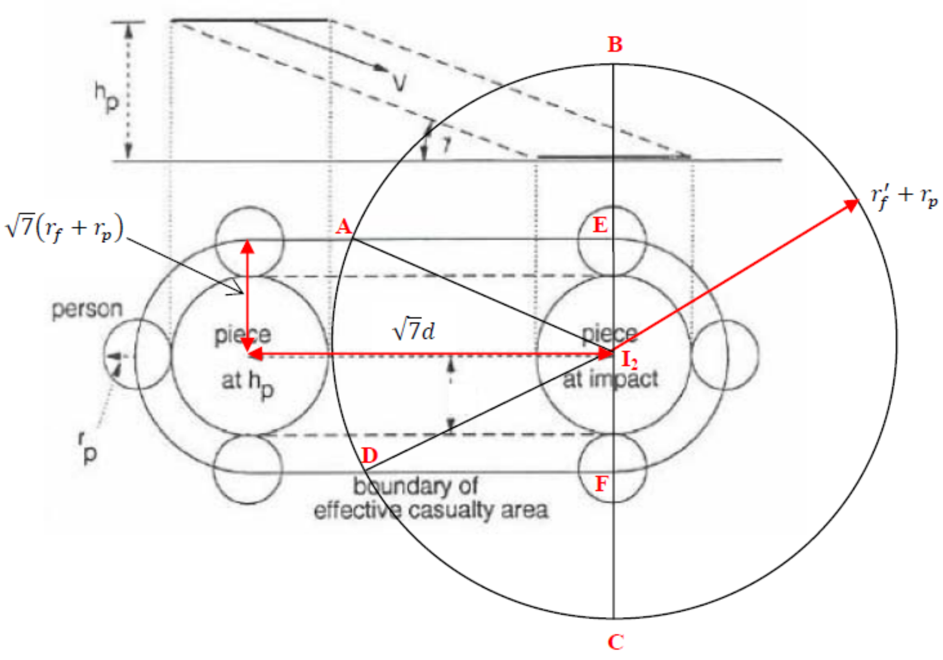


Figure A-3 – Scheme for the derivation of the basic area A_b' increased for taking into account the debris projection after impact. S = Area of Sector (I_2AB) = Area of Sector (I_2CD); T=Area of Triangle (I_2AE) = Area of Triangle (I_2FD); C = Area of Circle (I_2, r'_f+r_p).

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[6] The assumption that the detachment and projection of the parts begins from the RPA arrival point I_2 is conservative because it is be likely that the detachment took place at the first impact point I_1; in this last case the additional term (equal to the debris area in excess to the inert area) would be lower because there would be a greater amount of inert area inside the circle of radius $k_d r_f$+r_p centered at the impact point.

In formulas:

(A15) $$C = \tfrac{1}{2}\pi(k_d\cdot r_f + r_p)^2 - \tfrac{1}{2}\pi[\sqrt{7}(r_p + r_f)]^2 = \tfrac{\pi}{2}[(k_d\cdot r_f + r_p)^2 - 7(r_p + r_f)^2]$$

(A16) $$S = \tfrac{1}{2}(k_d\cdot r_f + r_p)^2 cos^{-1}\ [\tfrac{\sqrt{7}(r_p+r_f)}{k_d\cdot r_f + r_p}]$$

(A17) $$T = \tfrac{1}{2}\sqrt{7}(r_p + r_f)\sqrt{(k_d\cdot r_f + r_p)^2 - 7(r_p + r_f)^2}$$

Based on what said, the additional term is given by the following formula:

(A18) $$\Delta\ = C + 2S - 2T\ .$$

By introducing the expressions (A15), (A16) and (A17) into the formula (A18) we get:

(A19) $$\Delta = \tfrac{\pi}{2}[(k_d\cdot r_f + r_p)^2 - 7(r_p + r_f)^2] + (k_d\cdot r_f + r_p)^2 cos^{-1}\ [\tfrac{\sqrt{7}(r_p+r_f)}{k_d\cdot r_f + r_p}] +$$

$$- \sqrt{7}(r_p + r_f)\sqrt{(k_d\cdot r_f + r_p)^2 - 7(r_p + r_f)^2} =$$

$$= (k_d\cdot r_f + r_p)^2\{\tfrac{\pi}{2} + cos^{-1}\ [\tfrac{\sqrt{7}(r_p+r_f)}{k_d\cdot r_f + r_p}]\ \} +$$

$$- \sqrt{7}(r_p + r_f)[\tfrac{\pi\sqrt{7}}{2}(r_p + r_f) + \sqrt{(k_d\cdot r_f + r_p)^2 - 7(r_p + r_f)^2}]$$

We can thus express, in this case, in the corrected casualty area as:

(A20) $$A'_C = A_C + \Delta = A_{inert} + A_e + \Delta$$

Where the term Δ is given by the expression (A19), or

(A21)

$$A'_C = A_C + \Delta = 7[2(r_p + r_f)\tfrac{h_p}{tg\ \gamma} + \pi(r_p + r_f)^2] + \pi\cdot f\cdot K^2\cdot W^{\frac{2}{3}}\ +$$

$$+ (k_d\cdot r_f + r_p)^2\{\tfrac{\pi}{2} + cos^{-1}\ [\tfrac{\sqrt{7}(r_p+r_f)}{k_d\cdot r_f + r_p}]\ \} +$$

$$- \sqrt{7}(r_p + r_f)[\tfrac{\pi\sqrt{7}}{2}(r_p + r_f) + \sqrt{(k_d\cdot r_f + r_p)^2 - 7(r_p + r_f)^2}]$$

By substituting the numerical values inside the formula (A21), as previously done for the formula (A8), we get (always under the hypothesis of having gasoline or kerosene onboard as the unique potentially explosive material), we get (r_f=L/2):

(A22)

$$A'_c = 84\frac{(1+0.5L)}{tg\,\gamma} + 22(1+0.5L)^2 + 5.12\cdot f\cdot(V)^{\frac{2}{3}} + (2.5L+1)^2\{1.57 + cos^{-1}[\tfrac{2.65(0.5L+1)}{2.5L+1}]\} +$$

$$-2.65(0.5L+1)[4.16(0.5L+1) + \sqrt{(2.5L+1)^2 - 7(0.5L+1)^2}]$$

with [A'c]=ft^2, [L]=ft, [V]=lt.

Casualty area in the Case c)

If the (A13) is verified the corrected casualty area is thus given by the following:

(A23) $A'_C = A_{debris} + A_e = \pi[(k_d r_f + r_p)^2 + f\cdot(K\cdot W^{\frac{1}{3}})^2]$

where A_{debris} is given by the (A10) and $A_e = \pi\cdot f\cdot(K\cdot W^{\frac{1}{3}})^2$.

By substituting the values of the parameters, if the fuel is gasoline or kerosene, as above (k_d=5, r_f=L/2, r_p=1), we have then:

(A24) $A'_C = 3.14(2.5L+1)^2 + 5.12\cdot f\cdot V^{\frac{2}{3}}$.

with: [A'_C]=ft^2 , [L]=ft , [V]=lt.

The three cases are summarized below for easiness:

(A14) $A'_C = A_c = A_{inert} + A_e, \quad per \quad r_f + r_p \le \sqrt{7}(r_f + r_p)$

(A20) $A'_C = A_C + \Delta = A_{inert} + A_e + \Delta, \quad per \quad \sqrt{7}(r_f + r_p + d) > k_d\, r_f + r_p > \sqrt{7}(r_f + r_p)$

(A23) $A'_C = A_{debris} + A_e, \quad per \quad k_d\, r_f + r_p > \sqrt{7}(r_f + r_p + d)$

Appendix B

Probabilistic criteria for the buffer determination

This Appendix describes some acceptable criteria for determining the buffer. Different criteria, which lead to an equivalent (or greater) level of protection of the third parties on ground can be taken into consideration base-by-case by the Authority.

The buffer is here defined on the basis of the **Assumption (A2)** which requires that the RPA does not exit the buffer following a single failure or a single malfunction. Based on this assumption, in principle, the RPA could be allowed to exit the buffer following multiple failure and/or malfunctions, even though in such cases other safety barriers should intervene in order to minimize the related risk, as e.g. the activation of a FTS.

For the aim of the present methodology it is expected to take into account all and only those single failure and malfunctions which, starting from the nominal flight conditions foreseen by the approved flight envelope, could lead to an uncontrolled fall on ground both within[7] the authorized area of operations or outside this area (*excursion*).

The following steps should be followed for the buffer determination (see Figure B-1).

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[7] Defining the buffer also taking into account the uncontrolled falling on ground within the authorized area of operation is justified by the probabilistic approach followed here, which takes into account the uncertainty associated with the nominal position of the impact point. This means that, in principle, even if the nominal point of impact worked out form the equations falls inside the area of the operations, the area associated to its uncertainty (see the concept of "uncertainty radius" explained in the following) could also lay outside and beyond the area of operations, which should obviously be considered in the buffer determination. A typical situation is that in which the nominal impact point falls exactly on the border of the area of the operations: in this case it is evident that there is a certain probability that the actual impact point falls outside the area, and this should not be neglected.

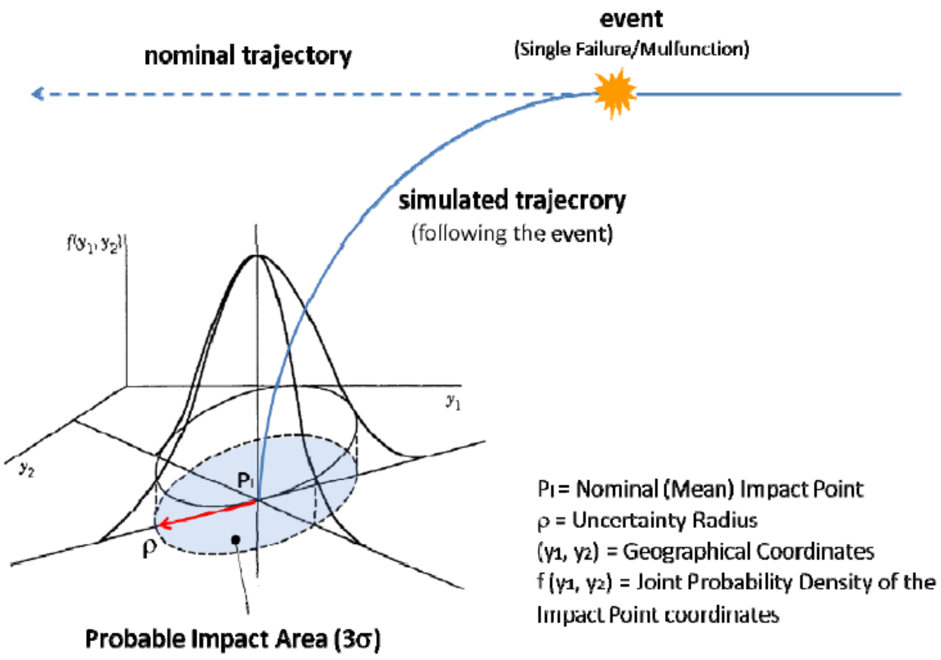

Figure B-1 – Probabilistic buffer determination. Main parameters.

1. Consider all possible nominal trajectories that can be flown within the authorized flight envelope over the authorized area of operations (which does not include the buffer). These trajectories can be grouped in different types, considering for the analysis only the most critical trajectory in each group. A critical trajectory is a trajectory where:

    (i) a single failure or malfunction leads the **nominal** RPA impact point as far as possible from the border of the authorized area of operations, or

    (ii) the parameters (e.g. the initial conditions) or the equations used are characterized by a level of uncertainty that could lead to a significant level of uncertainty on the geographical coordinates of the **actual** impact point, with respect its nominal position.

2. For each nominal trajectory (or for each critical trajectory) and for each point (instant) of the trajectory determine all possible **single** failure and malfunction (“event”) that could lead to an

uncontrolled falling on ground (including the uncontrolled falling on ground outside the authorized area of operations). This phase should be carried out by the Safety Assessment methodologies.

3. For each event defined at point 2. (i.e. single failure or malfunctions) carry out a simulation of the trajectory of the RPA or its parts (if the considered event leads to a parts separation in flight) in order to determine the nominal impact point on ground and the *uncertainty radius* related to it, as further specified. The trajectory simulation shall develop from the initial conditions existing at the time the event occurs. For the RPA or each part of the RPA that results from the event the simulation shall at least take into account the following parameters:
   (i) Initial position and attitude;
   (ii) Initial velocity vector;
   (iii) Ballistic coefficient;
   (iv) Thrust, Lift and Drag (or, in general, aerodynamic forces and moments);
   (v) Wind.

4. The position of the impact point on ground, of coordinates (X,Y), is considered as a vector random variable with a joint probability density f(x,y) on the coordinates X, Y (probability distribution).
   The trajectory simulation after an event has occurred aims at determining the nominal impact point on ground and the related uncertainty; however, due to the inherent random character of the variables involved, **the simulation must determine the probability distribution of the impact point** f(x,y) following an event that occurs in a certain point of the nominal trajectory. The probability distribution of the impact point on ground (better, the probability distribution of its coordinates) can be obtained by using one of the two alternative methodologies:
   a. The Monte Carlo Method, or
   b. The Covariance Matrix propagation of the coordinates[8]

5. Let P_I = (X, Y) the impact point. Once the P_I joint probability density f(x,y) has been determined it is possible to find, by integration, the "probable" impact region A_I defined as that geographical region such that there is a **probability of 99.7%** (corresponding to a **3σ confidence level**) that the actual impact point fall inside this area, i.e.:

   (B1) $Prob(P_I \in A_I) = \iint_{A_I} f(x,y)dxdy = 0.997$

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[8] The Covariance Matrix propagation method normally leads to a bivariate normal distribution of the impact point coordinates, which is easily treatable by analytical or numerical tools.

6. The **nominal impact point** $\overline{P}_I$ is determined as the **mean value of the of the impact point** P$_I$ having a probability distribution characterized by the probability density f(x,y), or

   (B2) $\overline{P}_I \equiv (\overline{X}, \overline{Y}) = (E[X],\ E[Y])$

   with

   (B3) $\overline{X} = E[X] = \iint x \cdot f(x,y)dxdy$

   (B4) $\overline{Y} = E[Y] = \iint y \cdot f(x,y)dxdy$

   where the integration is extended in principle to all the plane.

7. Once the probable impact region A$_I$ has been determined, the *uncertainty radius* related to the nominal impact point must be obtained. The **uncertainty radius** ρ_I related to the nominal impact point $\overline{P}_I$ is defined as the <u>maximum distance between the nominal impact point</u> $\overline{P}_I$ <u>and the border to the probable impact region A$_I$</u>. Let $C_I(\overline{P}_I, \rho_I)$ the **uncertainty circle**, defined as the circle centered at the nominal impact point $\overline{P}_I$ with a radius equal to the uncertainty radius ρ_I related to it.

8. The **buffer** is finally determined, as follows, based on the <u>envelope (I) of all the uncertainty circles</u> related to all the nominal (critical) trajectories, all the point of each trajectory, all events that could come out in each point of each trajectory, and that could lead to an uncontrolled flight on ground. All the parts in which the RPA could separate in flight following an event must be separately considered in this analysis.

   B = *Buffer*
   A$_{ops}$ = Area (region) of operations (authorized)
   I = Uncertainty circles envelope[9]

   Then the buffer B will be:

   (B5) $B = I - \{A_{ops} \cap I\}$

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[9] The envelope I is normally larger than the union ∪CI of the various uncertainty circles, being the area that envelopes them.

9. For the aims of the present methodology the buffer zone B must be characterized by the same (uniform) population density as the area of operations A_{ops} . For the aims of the risk analysis this is equivalent to consider an extended area of operations A'_{ops} given by the union of the authorized area of operations A_{ops} and the buffer B, or

   (B6) $A'_{ops} = A_{ops} \cup B = A_{ops} \cup I$