European Union Aviation Safety Agency	**PROPOSED** **Guidelines for the calculation of the critical area of Unmanned Aircrafts**	Doc. No. : **XX** Issue : 1 Date : Proposed ☒ Final ☐ Deadline for comments: 20 NOV 2023

SUBJECT	:	**SORA Step #2 – Intrinsic ground risk class**
Scope	:	**Definition of guidelines to calculate the critical area of Unmanned Aircrafts**
REQUIREMENTS incl. Amdt.	:	**AMC 1 of Article 11 of Regulation (EU) 2019/947**
ASSOCIATED IM/MoC	:	**Yes☐ / No ☐**

Table of Contents

Chapter 1: General

Section 1 - Background and Introduction

Step #2 of the SORA requires operators to assess the intrinsic ground risk class (iGRC) of their operations basing on the characteristic dimension, typical kinetic energy expected and the population density of the ground risk footprint. One of the factors contributing to the computation of the iGRC is the Critical Area of the UA, which may be defined as "*the sum of all areas on the ground where a person standing would be expected to be impacted by the UA during or after a loss of control event, and thus the area where a fatality is expected to occur if a person were within it*". This value is calculated basing on the characteristics of the UA together with additional parameters which affects the impact with the ground (impact angle, velocity, etc.).

As SORA is developed to cover a broad range of use-cases, the Critical Area calculation is modelled around the descent and crash model of a fixed-wing UA, as the critical area resulting from this kind of crash is bigger, and therefore more conservative, compared to other crash scenarios. This model will be referred in this document as the "JARUS Model".

These guidelines introduce a model to calculate the critical area resulting from a crash with a high impact angle (above 60 deg.) between the horizon and the trajectory of an UA in a ballistic descent. This scenario is typical of rotorcrafts and multirotor UA. This model will be referred in this document as the "High impact angle model".

The following assumptions should be satisfied to obtain a realistic representation of the critical area using with the ballistic model:

- The UA should not be capable of gliding;
- The impact angle of the UA with the ground should be higher than 60 deg.

These guidelines are not addressing the calculation of the critical area resulting from the application of an M2 mitigation (SORA Step #3), but refer to the critical area to be expected from the impact with the terrain of an UA with no ground risk mitigations applied (SORA Step #2).

Section 2: Definitions

	Definition
JARUS Model	The JARUS model is a combination of models to calculate the critical area of an aircraft which feature glide and slide.
High Impact Angle model	It is a model presented in these guidelines which may be used to assess the critical area of an UA resulting from a crash with an impact angle higher than 60º.
Impact angle	It is the angle comprised between the horizon and the speed vector of the UA at the moment of the impact with the terrain.
Critical Area	It is the sum of all areas on the ground where a person standing would be expected to be impacted by the UA during or after a loss of control event, and thus the area where a fatality is expected to occur if a person were within it.

Chapter 2: Overview of the scenarios

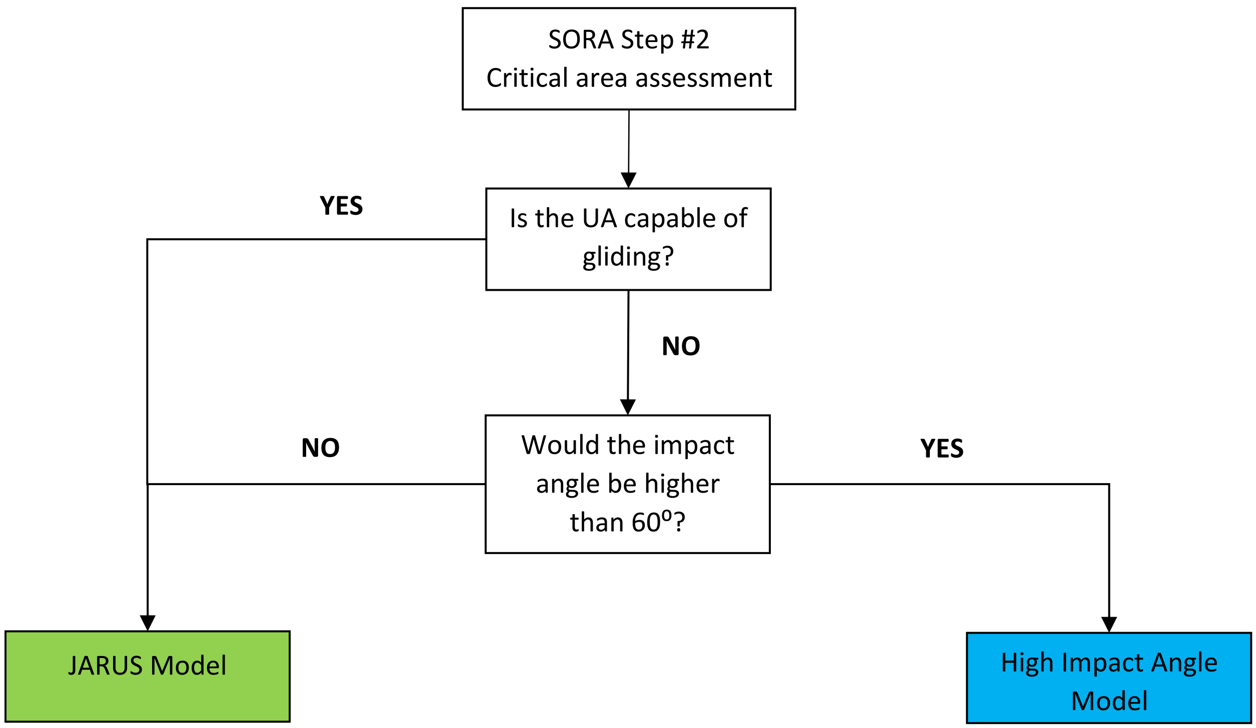
In these guidelines, two models are presented which are suitable respectively for two different impact scenarios:

- The JARUS model describes the impact of an UA which in case of a loss of power is gliding until reaching the terrain;
- The High impact angle model is describing a crash resulting from a free fall of the UA in case of a loss of power, and where the impact angle is so high such that the impact dynamics are different from the ones described in the JARUS model.

Therefore, the selection of one of the models over the other is defined basing on the following conditions:

1. Gliding capability of the UA;
2. Impact angle.

The following flowcharts gives an overview of how to select the most suitable model:



Chapter 3: Critical Area and intrinsic Ground Risk Class

Among the factors which define the intrinsic ground risk class (iGRC) of an UA is the size of its critical area. To each of the maximum UA characteristic dimensions reported in the iGRC table which are set as thresholds for the different iGRC values, is associated a Critical area value. These values are shown in the table below:

Max. characteristic dimension (m)	≤1	≤3	≤8	≤20	≤40
Critical area (m^2)	8	80	800	8000	80,000

Table 1

These values may be too conservative for some use cases, and the models and tool presented in these guidelines are mainly targeted for those scenarios. This can be the case for:

- UASQ which has a max. characteristic dimension which is slightly above one of the thresholds;
- large UAS which are however light-weight and with a low cruise speed.

The table above, taken from SORA 2.5 Annex F, should be used as a baseline to assess which is the suitable column of the iGRC table to be selected for a specific operation.

Using these guidelines, the applicant may calculate the critical area of the UA used in its operations and compare it with the content of Table 1. In case of mismatch between the max. characteristic dimension and the critical area size, the column associated with the calculated value of the critical area can be chosen to assess the iGRC (Table 2).

Intrinsic UAS ground risk class				
Max UAS characteristics dimension	1 m / approx. 3 ft	3 m / approx. 10 ft	8 m / approx. 25 ft	>8 m / approx. 25 ft

Table 2

Example:

The following example is carried out to show a practical use-case of what has been introduced above. For an UAS operator operating an UA with a 3.4 m, the following column should be chosen when performing SORA Step #2:

Intrinsic UAS ground risk class				
Max UAS characteristics dimension	1 m / approx. 3 ft	3 m / approx. 10 ft	8 m / approx. 25 ft	>8 m / approx. 25 ft

The applicant may calculate the critical area of its UA basing on the UA design and operational characteristics.
In this example, the applicant obtains a critical area of 74 m^2, which is smaller than the critical area threshold for UA with a max. characteristic dimension below 3 m. Therefore, the second column of the iGRC table may then be used:

Intrinsic UAS ground risk class				
Max UAS characteristics dimension	1 m / approx. 3 ft	3 m / approx. 10 ft	8 m / approx. 25 ft	>8 m / approx. 25 ft

Chapter 4: the JARUS Model for calculation of Critical area

The Jarus model uses as inputs the UA maximum characteristic dimension, MTOM and max cruise speed to calculate the critical area. The variables are used for a calculation of glide and slide area where a person would be potentially impacted by the UA.

Annex F introduces the simple critical area formula applicable for UAS sizes above 20m:

$$AC = 2\ rD\ (dglide + dslide{,}reduced) + \pi\ rD^2$$

Which is modified by an obstacle reduction factor for UAS sizes between 1m and 20m. The modified equation is then:

AC = Obstacle reduction * [2 rD (dglide + dslide,reduced) + π rD^2]

For UAS smaller than 1m in size the slide portion of the equation is taken out which modifies the equation for 1m UAS as follows:

AC = 2 rD (dglide) + 0.5*π rD^2

Where:

- $\mathrm{rD} = rperson + \frac{w}{2}$, with $rperson$ is the radius of a person and w is the wingspan (UAS characteristic dimension)
- $dglide\ (m) = \frac{hperson}{tan\theta}$, with hperson is the height of a person in meters and θ is the impact angle. The angle for ≤1m UAS is set to 35° and all larger UAS use an angle of 10°.
- dslide,reduced = e vhorizontal tsafe – 0.5 Cg g tsafe^2,
  - Vhorizontal = V cos Θ, where V is the maximum cruise speed for ≤1m UAS and the glide speed for all larger UAS.
  - Vglide = Vmax.cruise*0.65

  - $tsafe = \frac{Vnon_{\_lethal} - e\,Vhorizontal}{-Cgg}$, if tsafe < 0, then dslide reduced is set to 0

  - $Vnon_{\_lethal} = \frac{\sqrt{\mathrm{K\_non\_lethal}}}{\mathrm{m}}$, with Knon-lethal set to 290 J and m the mass.
  - Cg is the friction coefficient set to 0.65 and gravitational acceleration is 9.81 m/s^2
  - e = Coefficient of restitution which is 0.74 for 35° impact angles and 0.8 for 10° impact angles.

The model calculates the slide critical area which is assumed still lethal for an impact to the limbs.

Chapter 5: Overview of the High Impact Angle Model

Step 1: Pre-conditions for applicability of high Impact angle model

1. For an operator to claim the use of the High impact angle model to their operation the following two conditions must be applicable:
   a. The UAS used must be a powered lift aircraft without the capability to glide. i.e., a helicopter or a multirotor type design. Hybrid VTOL designs with wings are not applicable.
   b. The operational minimum altitude and maximum speed result in a calculated impact angle of more than 60 degrees according to the impact angle model calculator (see details of impact angle model in Annex).
2. If either of the conditions above is not complied with then the low impact angle model according to JARUS Annex F Mod EASA is to be applied.

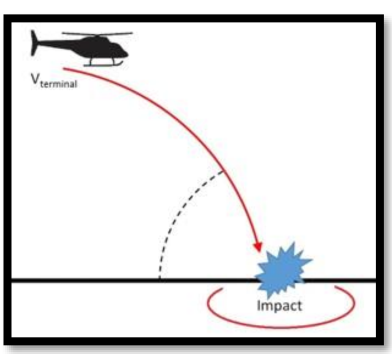
Step 2: Impact angle calculation

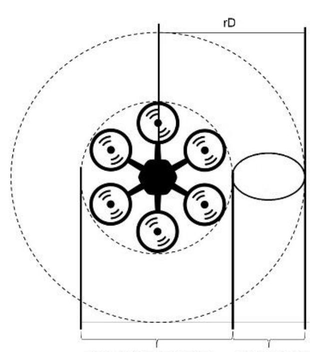
The calculation of the impact angle is an induction by time iteration. The induction begins for a given fight altitude and speed (Vno). For each iteration of time, the horizontal and vertical speed are calculated based on the drag force and a speed vector. The iteration ends when the UA reaches the ground. At this point the angle of impact is calculated. To calculate the impact angle the model uses as inputs the UA maximum characteristic, the UA mass, the maximum cruise speed and the flight altitude (for further details see annex including the mathematical model).

Step 3: Calculation of Ac - Model

The High impact angle model is assuming the critical area can be estimated by a circle defined by the radius of the characteristic dimension and a person multiplied by a safety factor between 2 to 7. The safety factor is calculated by an equation based on the kinetic energy of the UA calculated at terminal velocity. The terminal velocity calculation uses same aerodynamic assumptions as the impact angle calculator.

$$\boldsymbol{A_c = F_s * \pi * rD^2}$$

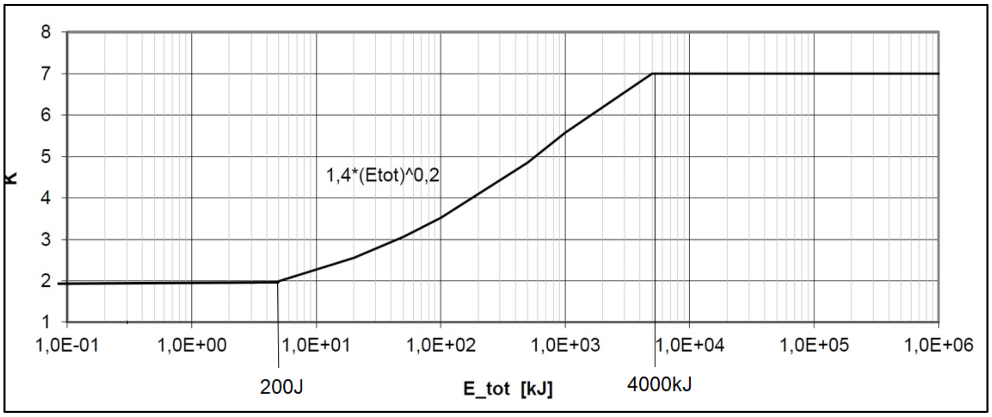




The safety factor[1] is assumed to include all bounce, blade throw and splatter effects from impacts with the UA. The formula is based upon FAA Advisory circular[2]. The lower limit of the safety factor was increased from 1.1 to 2 by the Deliverable 2 team to account for the 60-degree impact angle (rounded function in the tool) increasing the impacted area over a 90-degree impact angle.

Safety factor

F_s



	E_k	F_s
Lower limit	$\leq 0.2kJ$	2
Equation	$0.2kJ \leq E_k \leq 4000kJ$	$1.4 * E_k(kJ)^{0.2}$
Upper limit	$> 4000kJ$	7

Safety factor is calculated by the above equation and two limit values using the kinetic energy assumed at terminal velocity. Terminal velocity is calculated by the equations below using assumptions aligned with Annex F ballistic descent calculations. Terminal velocity was chosen for the calculation because SORA method should assume the worst credible case impact in the iGRC calculation.

$$E_{k.terminal} = \frac{1}{2} m {V_{terminal}}^2$$

[1] John A. Ball, Michael Knott, Dr. David Burke, “CRASH LETHALITY MODEL”, 2012;

[2] Advisory circular FAA AC-431.35-1

$$V_{terminal} = \sqrt{\frac{2mg}{\rho A C_d}}$$

ANNEX 1: Impact angle – mathematical model

The UA begins its descent from an **initial Vertical Distance (t)** (or Height [m]) at a maximum forward speed [m/s] = V0

The **induction** is done by **iteration of Δ t seconds each and ends** when the UA reaches the ground (when the vertical distance is equal to the minus initial Vertical distance):

Where

Vertical distance (t) = Vertical distance (t-1) + Vertical distance (t-1) * Δ t

With Vertical distance (0) = 0.

Where: Δ t is the induction time

<u>We define:</u>

$$\text{V horizontal(t)} = \frac{\text{V horizontal (t} - 1) + \text{Drag force Horizontal (t} - 1)}{\text{m} * \ \Delta \text{t}}$$

$$\text{V vertical (t)} = \frac{\text{V vertical (t} - 1) - (\text{g} - \text{Drag force Vertical (t} - 1))}{\text{m} * \Delta \text{t}}$$

Where

m = UA masse

$$\text{Drag Force horizontal (t} - 1) = \cos \Theta \ (\text{t} - 1) * \ \text{Drag Force} \ (\text{t} - 1)$$

$$\text{Drag Force vertical (t} - 1) = \sin \Theta \ (\text{t} - 1) \ * \ \text{Drag force} \ (\text{t} - 1)$$

$$\text{Drag Force (t} - 1) = 0.5 * \ \varrho * \ \text{Speed vector (t} - 1)^{\ 2} * \text{ref area} * \ \text{Cd}$$

Where:

ref area m^2 as per Annex F,

Cd = 0.8 (fixed as per Annex F),

ϱ = density of air and g= gravity

$$\text{Speed vector}(t-1) = \sqrt{V\ \text{horizontal}\ (t-1)^2 + V\ \text{vertical}\ (t-1)^2}$$

Where

$$V\ \text{vertical}\ (t-1) = \frac{V\ \text{vertical}\ (t-2) - (g - \text{Drag force Vertical}\ (t-2))}{m * \Delta\, t}$$

Since

$$V\ (t) = \sqrt{V\text{horizontal}\ (t)^2 + V\ \text{vertical}\ (t)^2}$$

$$\text{Tg}\ \Theta(t) = \frac{V\ \text{vertical}\ (t)}{V\ \text{horizontal}\ (t)}$$

Therefore:

$$\Theta\ (t) = \text{Arctg}\ \frac{V\ \text{vertical}\ (t)}{V\ \text{horizontal}\ (t)}$$

ANNEX 2: Tasksheet- Descriptions of deliverables for D2 project

Task designation	**Methodology to re-assess the critical area for the selection of the UA dimension (D2)**
Purpose and justification	1. To propose a simplified model to calculate the impact angle and additional models (to SORA Annex F) for the determination of the critical area, 2. To deliver a methodology for assessing the UA critical area for the selection of the correct UA size class (SORA 2.5 values are taken as reference), 3. The model does not repeal the current size classes of SORA, it proposes an alternative for cases for which the ground risk table leads to an excessive estimation of the UA critical area, 4. Lighter than air out of scope
Deliverable	1) Outline description of models for the calculation of the critical areas: 2) The models include: a) Calculation of realistic impact angles and the formulas to determine the critical areas, b) Calculation of critical area, two Scenarios: i) Scenario A: crash with high impact angle and ballistic descent, ii) Scenario B: crash with lower impact angle following Annex F assumptions. 3) Implementation of the models and availability of the tool in the EASA website as calculation engine for the use (free of charge) by industry and authorities. Note: • The mathematical model behind the tool shall not be visible in the EASA website, • The tool will return results (impact angle and critical area) based on the set of input variables provided by the user.
Plan / phases / target dates	• Step 1: Proof of concept based on dedicated examples for both scenarios (A and B see above) including: • Calculations of critical areas, • Selecting the correct UA size class based on calculated critical area. Step 2: availability of final models and tool on EASA website Target dates: TBD
Input documents	Regulation 2019/947-945 and AMC; SORA 2.0; SORA 2.5 package; Draft deliverable D1 of the AW TF; …
Additional information	It will have to be determined how to capture D2 under the EASA AMC to Article 11 of Regulation 2019/947. It should be defined if / how to exchange with JARUS