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Chapter 1: General

Section 1 - Background and Introduction

SORA Step #2 requires operators to assess the intrinsic ground risk class (iGRC) of their operations based on the characteristic dimension of the aircraft (as defined in SORA Annex I), typical kinetic energy expected (SORA 2.0), maximum cruise speed (SORA 2.5) and the population density of the ground risk footprint. One of the factors contributing to the computation of the iGRC table is the Critical Area of the UA, which is defined in SORA Annex I. This value is calculated basing on some technical specifications of the UA together with additional parameters which affect the ground impact (impact angle, velocity, etc.).

As the SORA methodology has been developed to cover a broad range of use-cases, the Critical Area calculation is modelled around the descent and impact model of a fixed-wing UA, as the critical area resulting from this kind of impacts is bigger and therefore may lead to a more conservative assessment of the iGRC, compared to other scenarios. This model will be referred in this document as the “JARUS Model”, and additional information on this model may be found in SORA Annex F.

This guideline is applicable to both SORA 2.0 and SORA 2.5. The main change in the ground risk assessment between the two versions is the transition from qualitative to quantitative indicators of the population density. However, the mathematical model driving the assessment of the iGRC remains the one defined in Annex F for both versions of SORA.

These guidelines provide an overview of the JARUS model and introduce an additional model to calculate the critical area resulting from an impact of an UA with the ground having an high impact angle (above 60 degrees). This scenario is typical of rotorcrafts and multirotor (ballistic descent). The latter model will be referred as the “High impact angle model”.

These guidelines do not address the calculation of the critical area resulting from the application of an M2 mitigation (SORA Step #3), but rather refer to the calculation of the critical area before mitigations are applied (SORA Step #2).

Lastly, this document comes in support to an online tool the “Critical Area Assessment Tool” available in EASA website. The tool computes the critical area for both models namely the Jarus Model and the High Impact Angle Model.

Section 2: Definitions

JARUS Model: the JARUS model is defined in Annex F of the SORA.

High Impact Angle model: 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: The impact is the angle comprised between the speed vector of the UAS and the ground at the moment of the impact with the ground.

Minimum Operational Altitude: the minimum operational flight altitude is the limitation in the operation manual outside takeoff and landing.

Chapter 2: Overview of the scenarios

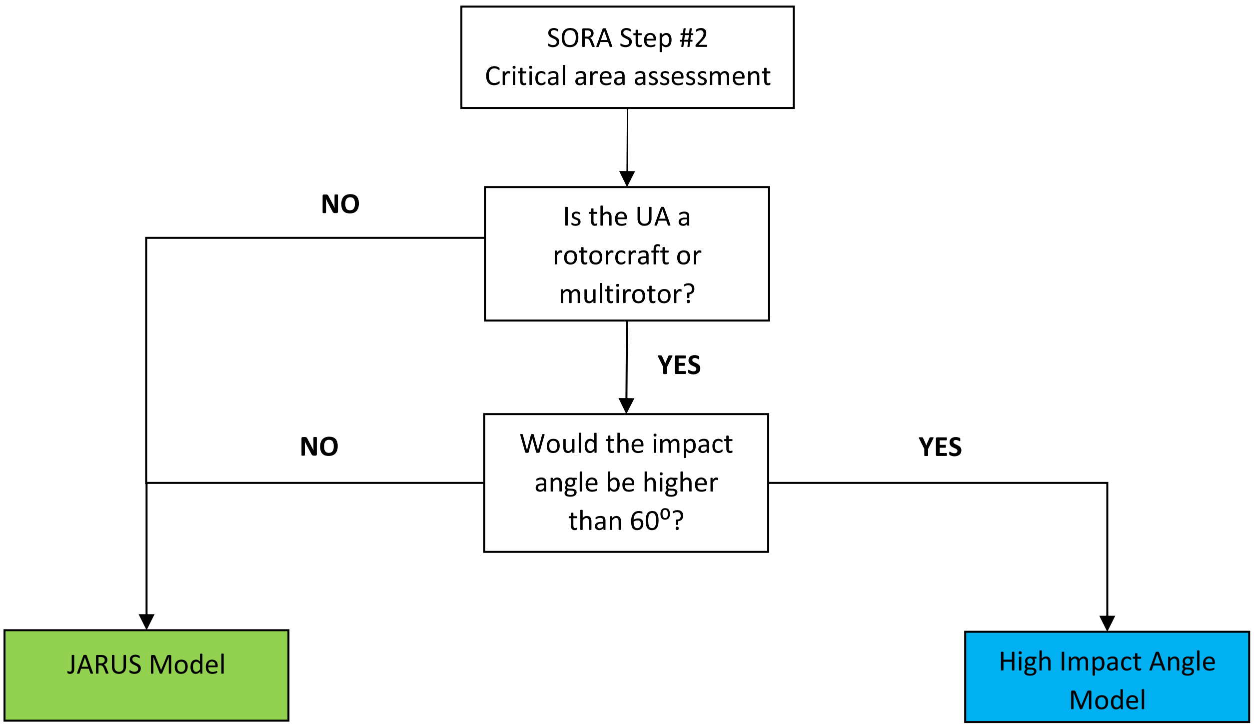
Two models are described to obtain the critical area of an UA, each of them represents a scenario:

- The JARUS model describes the impact with the ground of an UA with gliding capabilities until it reaches the ground.
- The High impact angle model describes a crash resulting from a ballistic descent of the UA and where the impact angle is so high such that the impact dynamics are different from the ones described in the JARUS model.

The selection of a model over the other is done based on the following conditions:

1. If the UA is a rotorcraft or multirotor.
2. If the impact angle is <= 60° or > 60°. The reason for choosing 60° as the threshold for using the impact angle model is to keep consistency with SORA Annex F. According to the annex, the typical ballistic impact angles from moderate altitude ranges between 50° and 70°, therefore 60° was chosen as a trade-off value.

The following flowchart provides an overview of the process for the selection of the applicable model:



The online Critical Area Assessment tool automatically performs the assessment above. The formulas used to calculate the impact angle resulting from a ballistic descent are reported in Annex 1 of this document.

Chapter 3: Critical Area and intrinsic Ground Risk Class

The size of the critical area is one of the factors defining the intrinsic ground risk class (iGRC). A critical area value is associated with each threshold of maximum characteristic dimension given in the iGRC table. These values are shown in the table below:

Max. characteristic dimension (m)	≤1	≤3	≤8	≤20	≤40
Critical area (m^2)	6.5	65	650	6500	65000

Table 1 – Critical area values

These values may be too conservative for some use cases therefore the JARUS model and high impact model target these scenarios.

- Example: UA with maximum characteristic dimension which is slightly above one of the thresholds;
- large UAs which are lightweight and have low cruise speed.

Using the EASA Critical Area assessment tool[1] , 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 – Max UAS characteristic dimensions

Example:

The following example is carried out to show a practical use-case. For an operator with a UA with a dimension of 3.4 m, the column highlighted should be chosen in 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

Table 3 – Selection of max UAS characteristic dimensions (example)

The applicant may calculate the critical area of its UA based on the UA design and operational characteristics. In this example, the applicant obtains a critical area of 62 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

Table 4 - Selection of max UAS characteristic dimensions (example)

[1] https://www.easa.europa.eu/en/domains/drones-air-mobility/drones-air-mobility-landscape/innovative-air-mobility-hub

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 (CA). The variables are used for a calculation of a glide and slide area where a person would be potentially impacted by the UA.

The formulas used to calculate the critical area with the JARUS model are below defined. EASA has consulted JARUS to use the latest developments in terms of model and value of parameters.

- **Case 1 - UA with a characteristic dimension above 8 meters**

$$AC = 2\, rD \left(D_{glide} + D_{slide,reduced}\right) + \pi\, rD^2 \tag{1}$$

- **Case 2: UA with a characteristic dimension greater than 1 meter and smaller or equal than 8 meters**

$$AC = Obstacle\ reduction * [2\, rD \left(D_{glide} + D_{slide,reduced}\right) + \pi\, rD^2] \tag{2}$$

- **Case 3: UA size smaller or equal than 1 meter**

$$AC = 2\, rD \left(D_{glide}\right) + 0.5\,(\pi\, rD^2) \tag{3}$$

Where:

$$rD = r_{person} + \frac{w}{2}, \tag{4}$$

with r_{person} the radius of a person and w is the wingspan (UA characteristic dimension)

$$D_{glide}\,(m) = \frac{h_{person}}{\tan(\theta)}, \tag{5}$$

with h_{person} the height of a person in meters and θ is the impact angle.

$$d_{slide,reduced} = e\, V_{horizontal}\, t_{safe} - 0.5\, C_g\, g\, t_{safe}^2 \tag{6}$$

$$V_{horizontal} = V \cos\Theta \tag{7}$$

where V is the maximum cruise speed

$$Vglide = Vcruise \tag{8}$$

$$t_{safe} = \frac{Vnon\_{lethal} - e\,Vhorizontal}{-Cgg}$$, if tsafe < 0, then dslide reduced is set to 0 (9)

$$Vnon\_{lethal} = \sqrt{(2\,K_{non_{lethal}})/m}$$, with Knon-lethal set to 290 J and m the mass (10)

The following constants are used for the different cases, which are aligned to the values used in SORA Annex F:

rperson (radius of a person)	***rperson***= 0.3 m (radius of a person)
h*person* (height of a person)	**h*person***= 1.8 m (height of a person)
e (coefficient of restitution)	**e** = 0.65 (coefficient of restitution)
θ (impact angle)	**θ** = 35° (impact angle)
Cg (coefficient of friction)	**Cg**= 0.75 (coefficient of friction)
g (gravitational acceleration)	**g**= 9.81 m/s² (gravitational acceleration)
Knon-lethal (non-lethal limb kinetic energy limit)	**Knon-lethal** = 290 J non-lethal limb kinetic energy limit.
Π	π = 3.14
C_d (drag coefficient)	C_d = 0.8
Obstacle reduction	Obstacle reduction= 0.6

Table 5 - Constants

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 rotorcraft or a multirotor, i.e., 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 assessment tool (see details of impact angle model in Annex).

   Note 1: If the hight impact angle is selected to assess the critical area then the operational minimum altitude should be set as a limitation in the operator's manual.

   Note 2: In case the operator opts to use the results of the high impact angle model, then they should iterate to find the minimum flight altitude that passes the threshold with the assessment tool.
2. If either of the conditions above not met, then the low impact angle model according to JARUS Annex F is to be applied.

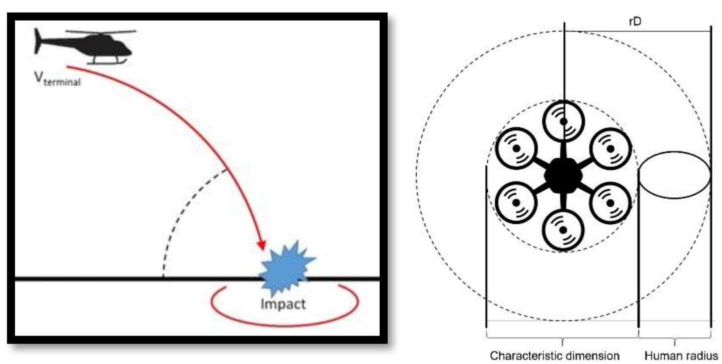
Step 2: Impact angle calculation

The calculation of the impact angle is an induction by time iteration. The induction begins for a given flight 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 assumes that the critical area can be estimated by a circle defined by the radius of the characteristic dimension of a person multiplied by a safety factor between 2,3 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 the same aerodynamic assumptions as the impact angle calculator.

$$A_c = F_s * \pi * rD^2 \qquad (11)$$



The safety factor[2] is assumed to include all bounce, blade throw and splatter effects from impacts with the UA, and the formula is based upon a military norm [3]. The lower limit of the safety factor was increased from 1.1 to 2.3 following the testing of the model using digital simulations.

[2] John A. Ball, Michael Knott, Dr. David Burke, "CRASH LETHALITY MODEL", 2012;

[3] "Omologazione, certificazione e qualificazione di tipo militare, idoneita' alla installazione", Ministero della difesa.

Safety factor

	$\boldsymbol{E\_tot}$	$\boldsymbol{F_s}$
Lower limit	$< 12\ kJ$	2.3
Equation	$12\ kJ \leq E_{tot} \leq\ 3125\ kJ$	$1.4 * E\_tot^{\ 0.2}$
Upper limit	$> 3125\ \ kJ$	7

Table 6 - Safety Factor calculation table

The safety factor is calculated by the above equation, and it ranges between two limit values. The kinetic energy is calculated conservatively assuming that the UA falls at terminal velocity. Terminal velocity is calculated by the equations below using assumptions aligned with Annex F. Terminal velocity was chosen for the calculation because SORA method should assume the worst credible case impact in the iGRC calculation.

$$E_{k.terminal} = \frac{1}{2} m V_{terminal}{}^{2} \tag{12}$$

$$V_{terminal} = \sqrt{\frac{2mg}{\rho A C_d}} \tag{13}$$

The terminal velocity is automatically calculated by the tool, and the factor "A", representing the frontal area, is calculated starting from the values provided in Annex F, which gives an estimation of the frontal areas for each characteristic dimension, according to the following table:

ANNEX F reference values					
Characteristic Dimension (m)	1	3	8	20	40
Frontal Area (m^2)	0.1	0.5	2.5	12.5	25

Table 7 - Frontal Area

The area used to calculate the terminal velocity is linearly interpolated starting from the values shown in the table.

ANNEX 1: Impact angle – mathematical model

The UA begins its descent from an **initial Vertical Distance fixed at zero [m]** (or Height [m]) at a maximum forward speed [m/s] = V(0) (=maximum cruise speed).
i.e. we put the origin of the axes at the height of the UA when it begins its descent.
So vertical distance (0) = 0.

If we set Δ t= the time step

We calculate :

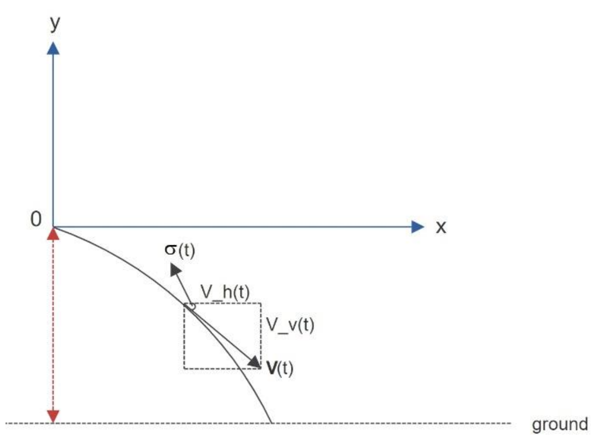
Vertical Distance (t) = Vertical Distance (t-1) + 0.5(Vertical Velocity (t-1) +Vertical Velocity (t)) * Δ t (14)

In simplified notation:

Vertical Velocity (t) = $V_{vertical}\ (t)$ (= $V_v(t)$, in the graph below)

Horizontal Velocity (t) = $V_{horizontal}(t)$ (= $V_h(t)$, in the graph below)

Vertical Distance (t) = Vertical Distance (t-1) + 0.5 ($V_{vertical}$ (t-1) + $V_{vertical}$ (t)) * Δ t (15)



The iteration ends when the vertical distance (t) = - height (when the UA touches the ground).

(Note that the vertical velocity < 0)

<u>We calculate at each step of the iteration:</u>

$$V_{horizontal}(t) = V_{horizontal}(t-1) + \frac{Drag\ force\ horizontal\ (t-1) * \Delta\ \mathrm{t}}{m} \tag{16}$$

$$V_{vertical}(t) = V_{vertical}(t-1) - \left[g - \frac{Drag\ force\ vertical_{(t-1)}}{m}\right] * \Delta\ \mathrm{t} \tag{17}$$

$$V_{vertical}(t) = V_{vertical}(t-1) - g.\Delta\ \mathrm{t} + \frac{Drag\ force\ vertical_{(t-1)}}{m} * \Delta\ \mathrm{t} \tag{18}$$

Where

$$\text{Drag Force horizontal } (\mathrm{t}-1) = \cos\Theta\ (\mathrm{t}-1) * \text{ Drag Force } (\mathrm{t}-1) \tag{19}$$

$$\text{Drag Force vertical } (\mathrm{t}-1) = \sin\Theta\ (\mathrm{t}-1) * \text{ Drag force } (\mathrm{t}-1) \tag{20}$$

$$\text{Drag Force (t-1)} = 0.5\,.\,\varrho\,.\,V\ (t-1)^2\ .\ A\,.\,Cd \tag{21}$$

Where:

A is the frontal area of the UA expressed in m^2 as per Annex F,

Cd = 0.8 (fixed as per Annex F),

ϱ = density of air and g= gravity

As

$$\mathrm{V\ (t)} = \sqrt{\mathrm{Vhorizontal\ \ (t)^2 + V\ vertical\ (t)^2}} \tag{22}$$

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

We calculate:

$$\Theta\ (\mathrm{t}) = \mathrm{Arctg}\ \frac{\mathrm{V\ vertical\ (t)}}{\mathrm{V\ horizontal\ (t)}} \tag{23}$$

Variable	Unit	Description
A	m^2	Drag area for aircraft (area of aircraft projected along direction of travel)
A_C	m^2	Critical area
C_d	-	Drag coefficient for aircraft

C_{g}	-	Friction coefficient between aircraft and ground
d_{glide}	m	Glide distance (horizontal distance)
d_{slide}	m	Slide distance
e	-	Coefficient of restitution
h_{person}	m	Height of a person
$K_{\mathrm{non-lethal}}$	J	Non-lethal kinetic energy
ρ	kg/m^3	Air density
r_{person}	m	Radius of a person
r_{D}	m	'Radius' of the critical area
θ	def	Impact angle (between direction of travel and ground)
v	m/s	Impact velocity (in the direction of travel at impact)
$v_{\mathrm{horizontal}}$	m/s	Horizontal speed (horizontal component of v)
$v_{\mathrm{non-lethal}}$	m/s	Non-lethal velocity
w	m	Wingspan (size of aircraft orthogonal to direction of travel)