Unmanned Aircraft Systems Risk Assessment: Review of Existing Tools and New Results

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ABSTRACT

This paper outlines a review of the relevant civil and military regulation applicable to Unmanned Aircraft Systems (UAS) and establishes a comparison between current relevant UAS risk assessment frameworks, viz., JARUS SORA, FAA Risk Index, EDA Risk Assessment Tool (RAT). Furthermore, this research presents a thorough, yet innovative, methodology for the assessment of risk in the operation of UAS with the goal of assisting the decision-making process of airworthiness authorities in the issuance of permits to fly, the pRAT. It is concluded that SORA is the most holistic methodology, due to the consideration of ground and air risk, added to the consideration of energy and UAS specific characteristic; despite simpler, the FAA order focuses of risk categories associated with UAS and operation location characteristics, still presenting an elevated potential for standardization; the pRAT approach builds on the RAT and focuses in obtaining answers of a design integrity checklist specially programmed to provide clear insight on the design safety of the UAS, however lacks on the lack of human factors and air risk class. . The RAT was found to have a profound analysis of the design integrity of the UAS, however, it lacks on means of compliance, operational aspects and air risk classification.

1.0 INTRODUCTION

Although inspired on manned aircraft operations, the operation of Unmanned Aircraft Systems (UAS) differs from the former in various aspects, from which the airworthiness certification requirements take a predominant position. Airworthiness certification is carried to assure an acceptable level of safety of an aircraft. While, for manned aircraft, such safety levels are commonly accepted, for their unmanned counterparts there is still not a consensus, namely for smaller size UAS. Currently, a manned aircraft must be certified as airworthy according to existing airworthiness specifications in order to operate. The existing UAS airworthiness specifications are the STANAG 4702 [1], STANAG 4703 [2] and STANAG 4671 [3], which tend to not be used by the relevant stakeholders due to the level of demand required. In addition, MIL-HBK-516 [4] comprises the Airworthiness Certification Criteria, including criteria for UAS. Conversely, the airworthiness certification of UAS typically uses a different approach which is dependent on the risk that it poses to ground and third parties.

If, on the one hand, certification requirements of UAS were developed and standardized to ensure that and acceptable level of safety of UAS is achieved; on the other hand, there is evidence that suggests the non-adoption of such requirements as these are considered too onerous for the development and lifecycle support of a small UAS. Bearing in mind that small UAS – up to 150kg of Maximum Take-off Weight (MTOW) – are responsible the greater percentage of uses in UAS operations, and that these systems typically have a reduced applicability scope and lifecycle, it becomes evident that the compliance of the existing UAS certification specifications become too demanding for majority systems

As a result, several international agencies have collaborated in the development of frameworks that aimed at circumventing the need for airworthiness certification of UAS, while still guaranteeing the required level of safety of the systems. These frameworks are based on the assessment of the risk that is inherent to the operation of a specific UAS, by an operator, in a designated location in time.

Despite a similar interpretation of the needs, the risk assessment frameworks that have been developed thus far have focused on different aspects of the operation for the assessment of the risk of operating an UAS. While some focus on the integrity of the UAS, with only a little consideration on the operational aspects of the mission; other focus on the standard operation scenario, risk mitigation or tactical strategies, operational safety objectives and operational limitations for that specific scenario. Such aspects make it difficult to develop and agree on a specific framework suitable for risk assessment, as well as to an approach for the harmonisation among regulatory and airworthiness authorities.

Due to the UAS market growth, small UAS are used both by military and civil operators [5]. This dual use characteristic contributes to a reduction of the cost of the UAS for the military, given the need for reduced-cost civil UAS operations. Therefore, the military community should act and determine how to assess such UAS and, consequently, issue permits to fly under specific requirements, since airworthiness certification of such platforms is far too demanding for UAS which are intended to be used in specific scenarios, for considerably small time periods.

The research methodology employed of the present work relies mainly on a thorough literature review. This article compares the advantages and drawbacks of several risk assessment frameworks for UAS, which include JARUS's Specific Operations Risk Assessment (SORA), FAA Order 8130.34D (Risk Index), and European Defence Agency (EDA) Risk Assessment Tool (RAT). Furthermore, the research presented brings a novel tool for the risk assessment of UAS, developed with the goal of aiding in the assessment of the risk inherent to the operation of a UAS, by a given operator on a pre-specified location, hence simplifying the assessment needed to meet the requirements of the issuing of a permit to fly by the National Airworthiness Authorities (NAA). This framework was based on the RAT framework, and implements new ways of assessing the risk, integrating it with a simple to use questionnaire to evaluate the probability of catastrophic failure, which is used to compute the probability of the UAS to hit a person or infrastructure on the ground.

2.0 SPECIFIC OPERATIONS RISK ASSESSEMENT

The SORA methodology, developed within Joint Authorities for the Rulemaking of Unmanned Systems (JARUS), was publicly presented in 2015, with the final annexes revealed to public on the External Consultation which ended in August 2018 [6]. The SORA is a step-by-step process [7], and encompasses the assessment of the risk into the ground and air risk categories, for the operation of UAS. The process comprises the analysis of the Concept of Operations, the evaluation of the ground and air risk classes, determination of the specific assurance and integrity level (SAIL). The output of this methodology is approval (or not) of the operation, using the identification of the recommended operational safety objectives with their level of robustness.

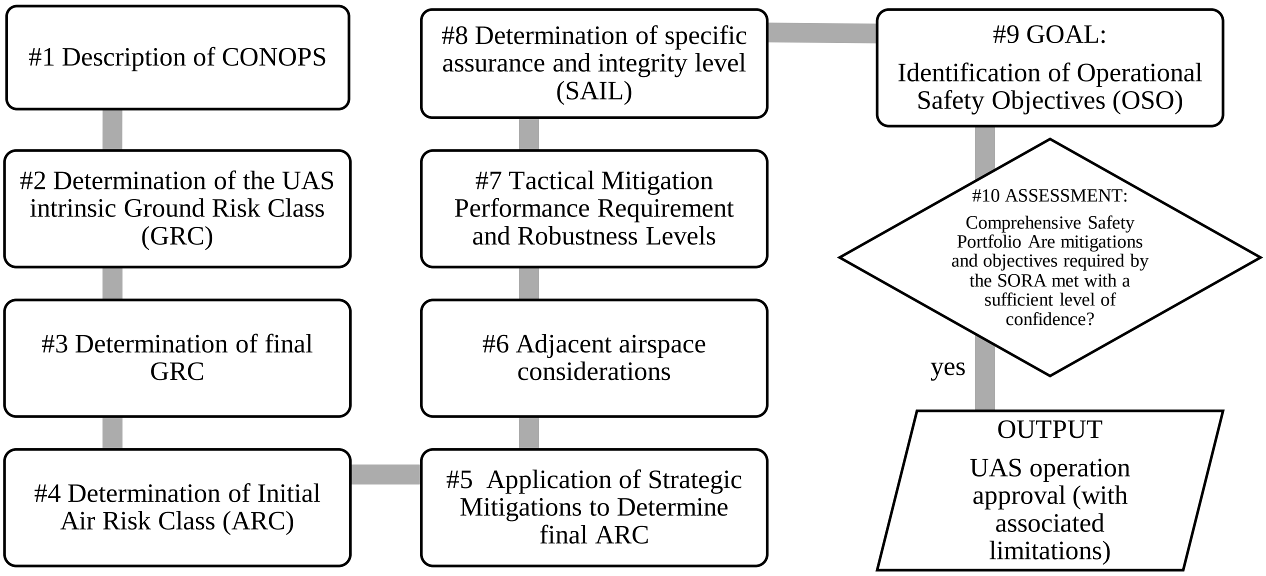


Figure 2-1 – SORA Process Outline. Adapted from [6, p. 17]

The ground risk class is a function of the maximum dimension characteristics the UAS, usually, wingspan or blade diameter, kinetic energy and operational scenarios. Depending on the harm barriers available for the UAS operation, the ground risk class could increase or decrease. UAS with a ground risk class of 7 or more are outside the scope of SORA. The determination of the SAIL is function of the ground risk class air risk class.

The air risk class depends on the airspace encounter categories. The four categories are: i) the integrated airspace operations above 500 ft; ii) the very low level (VLL) operations below 500 ft; iii) the very high level operations; iv) the operations in atypical airspace.

Strategic mitigations can be applied to decrease the encounter rate and therefore of the ARC. Operation restrictions of time, space, time of exposure and separation procedures are the strategic mitigations that can be adopted. The determination of the ARC is function of the operational strategic mitigations. In addition, tactical mitigations can be applied to assure that the residual risk of the ARC is met.

The recommended operational safety objectives depend on the highest SAIL obtained from the Ground Risk class and from the Air Risk Class. The identification of such recommended operational safety objectives required to ensure the safety of the UAS operation are related with technical issues of the UAS, human error, and the deterioration of external systems supporting the UAS operation.

An evident advantage of the proposed framework is the capability of considering ground and air risk classes in the categorization and classification of the OSO. This stands out as the most important feature of the SORA, since all aspects related to risk and safety regarding people on the ground and other aircraft in the same airspace are considered, hence making the SORA a very complete framework – this same aspect is not considered in the frameworks described in the following sections.

3.0 RISK INDEX – FAA ORDER 8130.34D

Airworthiness certification of UAS and Optionally Piloted Aircraft (OPA) regulated by FAA Order 8130.34D uses the risk index to identify the certification tasks needed to issue a special airworthiness certification or special permits to fly for UAS used in R&D, market survey, crew training and production flights. The current version of the FAA Order 8130.34D establishes step-by-step [8] procedures to issue special permits to fly for UAS and optionally piloted aircraft. It also introduces a risk-based approach to determine the certification tasks required for the certification process of the UAS.

The group risk category is calculated as a result of the analysis of the information of the flight area, the program letter and the safety checklist, when required. Such risk group category leads to the identification of the required certifications task as function of risk evaluation. A group risk category is a point-based methodology. Four categories of risks, comprising performance and operational parameters, are used. Such categories are maximum take-off weight, maximum speed, maximum operating speed and flight history. Total score is the sum of the points of the correspondent elements selected for each risk category. The risk categories, the incremental elements and the correlated points are illustrated in Table 3-1.

Table 3-1 – FAA Order 8130.34D – Risk Category

Risk Category	Incremental Element	Value
MTOW	Up to 4.5 lbs	0
	4.5 up to 55 lbs	5
	55 lbs up to 300 lbs	10
	300 lbs up to 1,000 lbs	15
	Greater than 1,000 lbs	25
Maximum Speed	Less than 87 kts	0
	87 kts to 250 kts	10
	Greater than 250 kts	20
Maximum Operating Altitude	Less than 200 ft AGL	0
	200 ft AGL up to 500 ft AGL	5
	500 ft AGL up to 5,000 ft AGL	10
	5,000 ft AGL up to 17,999 MSL	15
	Class A and above	25
Flight History	previous flight time ≥ 50 hrs	0
	previous flight time < 50 hrs	2
	Unknown – first flight	6

Three group risk categories with different ranges of values are illustrated in Table 3-2.

Table 3-2 – FAA Order 8130.34D – Risk Group Category

Group Category	**Total Score**
Group I	0 to 16
Group II	17 to 39
Group III	40 and above

In night operations, beyond visual line of sight, instrument meteorological conditions, extended visual line of sight, chase aircraft or operation closer than 2 miles from towered airport the Group III requirements applies. The certification tasks identified comprise chartered flight area, safety checklist, initial flight test plan, flight test plans for major configuration changes, operating manual, weight and balance, maintenance and inspection programme, maintenance record, condition inspection, compliance with airworthiness directives, major configuration change report are the certification tasks. The safety checklist, initial flight test plan, flight test plans for major configuration changes are not required for the Group Risk Category I.

The Maintenance and Inspection programme review and acceptance is not required for Group Risk Category I and II, however it is required a self-certifying statement of compliance with a maintenance and inspection program. A condition inspection is not required for UAS with MTOW less than 25 Kg.

4.0 RISK ASSESSMENT TOOL

UAS Airworthiness Regulatory Framework Working Group (UAS ARF WG) was created in 2014 under the auspices of European Defence Agency (EDA) to develop harmonised requirements, common classification and certification process [9]. This working group classifies the UAS within three categories based on risk which are low, medium and high risk, and has developed a Risk Assessment Tool (RAT) and a template of a safety case for small UAS. This tool has the background of STANAG 4703 and is based on a risk matrix, which combines the probability of the loss of the UAS with the probability of hitting people on the ground. The calculation of the probability of loss of the UAS is calculated as function of the UAS design integrity score using a point-based methodology. The RAT methodology is composed of three consecutive phases: I) Determine the Design Integrity Assessment Checklist (DIAC) score; II) Correction of the score from the DIAC, affecting it with negative impact based on the cross-relation of different factors on each domain of the DIAC; III) Determine the probability of hitting people on the ground.

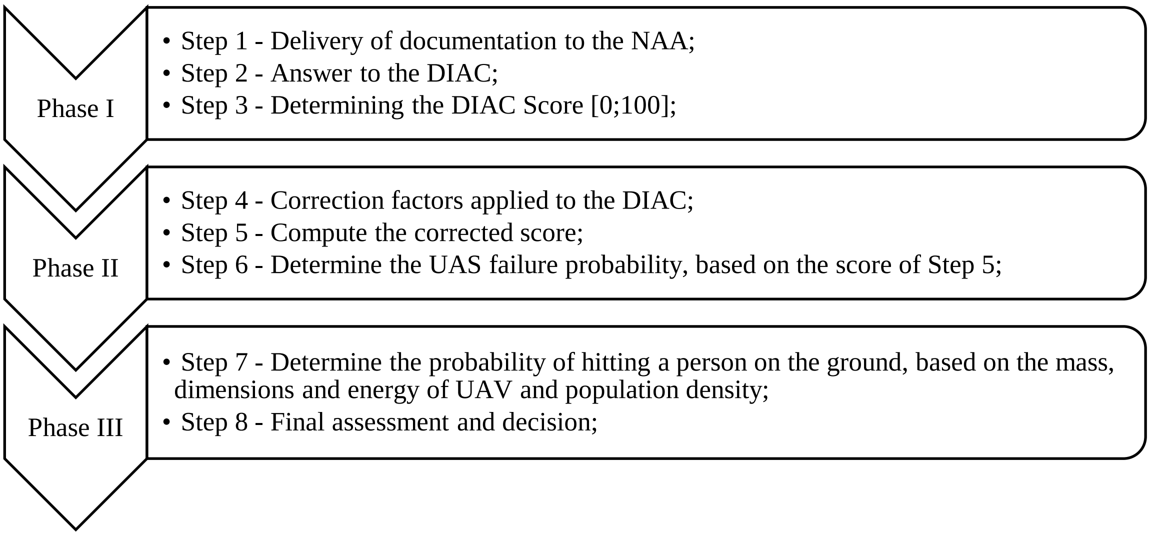


Figure 4-1 – Sequence Risk Assessment Tool

4.1 Phase I

After the application for a flight authorization has been submitted, the DIAC is assessed on the basis of the response to 65 questions and evaluation criteria, by demonstrating, through documentation or proof of tests carried out by the tenderer, concerning eleven areas: 1) Organization / Manufacturer; 2) Adopted Design Standards; 3) Tested Usage Spectrum; 4) Stability, Control and Emergencies; 5) Remote Control Station; 6)

Structural Integrity; 7) Propulsion and Feeding System Integrity; 8) Integrity of Systems and Equipment; 9) Safety Demonstration; 10) Software Integrity; 11) Continued Airworthiness and Operational Suitability. From the CAID results a score is evaluated, which in turn is used as the basis for estimating the probability of failure of UAS.

The maximum score of the DIAC is 100 points. If a quantitative Fault Tree Analysis (FTA) presents a cumulative probability of catastrophic event is higher than 1E-4, the total score is penalised by removing points. If an FTA is not presented, the total score penalisation can be reduced when fail-safe design, fault isolation, fault detection and fault management are included. It is required to evaluate the answers of the DIAC questionnaire and validate data in order to determine the score per domain and calculate the total initial score, which is the sum of the initial scores per domain. The calculation of the initial total score is expressed by:

$$Total\ Score_{(1)} = \sum \left(Domain\ Score_{(1)}\right)_{(i)} \tag{1}$$

4.2 Phase II

A correction factor matrix was established to reduce the score of specific domains with cross-domain items whose absence will have a negative impact on the reliability of that domain. Such relevant items are: a) Quality Assurance System; b) Technical Occurrence Tracking; c) Configuration Management; d) Human Machine Interface; e) Structural Integrity; f) Propulsion integrity; g) Electromagnetic Environment Effects (E3); h) FTA; i) Fail-safe functionalities; j) Software of life Cycle Assurance; k) Instructions for continuing and continued airworthiness.

At this step the probability of a catastrophic failure is estimated using:

$$P_{cat} = 0.1\ e^{-0.069.Score} \tag{2}$$

Which outputs a value of 1E-1 if score is 0, and 1E-4 if score is 100.

4.3 Phase III

The last phase is dedicated to computing the probability of hitting someone on the ground, in the case of catastrophic failure. Such probability if a function of the area of debris, which depends on the wingspan, speed, maximum take-off weight of the platform and population density. The probability of hitting people on the ground is calculated as:

$$P_{Hit} = A_{debris} \times P_{Den} \tag{3}$$

Where

P_{HIT} – Probability of hitting people on the ground; A_{debris} – Crash/Impact area [m^2];
P_{Den} – Population density [people/m^2].

The Crash/impact Area is calculated as:

$$A_{debris} = K \times b^2 \tag{4}$$

$$K = min[50\,; E \times 17{,}5 + 3{,}2858] \tag{5}$$

b – Wingspan [m];

The kinetic impact energy of the UAS is calculates as:

$$E = 0{,}5 \times m \times V^2 \tag{6}$$

Where

E - kinetic energy of the UAS at impact [J], m – UAS mass [kg]; V – UAS impact velocity [m.s-1];

This tool is based on the risk matrix which combines the probability of the loss of the UAS versus the probability of hitting people on the ground. The risk equation is calculated as:

$$R = P_{cat} \times P_{HIT} \times (1 - S) \quad (7)$$

Where

R – Risk equation; P_{cat} – Probability of catastrophic event; S – Shelter factor.

Shelter factor is a dimensionless value between 0 and 1 to estimate the exposure of the population to the UAS or its debris. A value of 1 means that the population is completely sheltered, whereas a value of o means that population is completely exposed. Such risk equation is based on the adaptation of the Casualty Expectation Equation based on the Range Commanders Council Supplement to document 323-99 [10]. Different ranges of risk can be defined in order to build a ground risk matrix. An example of the risk matrix ranges is presented in Table 4-1: Risk Criticality Ranges.Table 4-1.

Table 4-1: Risk Criticality Ranges.

Risk criticality	Risk criticality ranges
Unacceptable	>1E-3
Very High	>1E-4
High	1E-5 to 1E-4
Medium	1E-6 to 1E-5
Low	1E-7 to 1E-6
Very Low	<1E-7

Despite the potential of the RAT, the authors have found the RAT tool to be lacking on important aspects, out of which, we highlight: i) high complexity of the framework, derived by a lack of objectiveness in the criteria; ii) absence of previously defined means of compliance (MoC) for each criterium; iii) framework is agnostic to the mass of the UAS, which means that a system with 2kg is handled in the same way as a 150kg system; iv) absence of a computational tool which allows for the user-friendly answer of the DIAC; v) inexistence of a study case that allows for the comparison and validation of the methods.

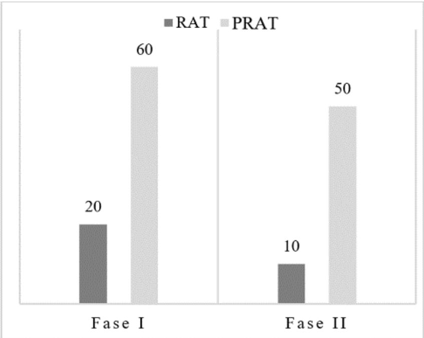
5.0 PROPOSED RISK ASSESSMENT TOOL

Despite the potential of the RAT for UAS safety and integrity assessment, its objectiveness and clarity need improvements. In particular, the following developments were introduced in the methodology: i) the requirements of the DIAC were clarified and separated into single unequivocal questions, currently totalizing 103; ii) specific MoC were created for each question; iii) UAS characteristics and concepts of operation were introduced in the DIAC and are used to compute the score, in such way that, e.g., inexistent FTA will have less impact on the final score for a 2kg UAS, when compared with a 35kg UAS; iv) the DIAC was implemented in open source software and the score is automatically computed. These developments were tested by a sample of six international military airworthiness authorities using a 35kg maximum take-off mass, 4.2m span UAS test case with proven experience in Portugal.

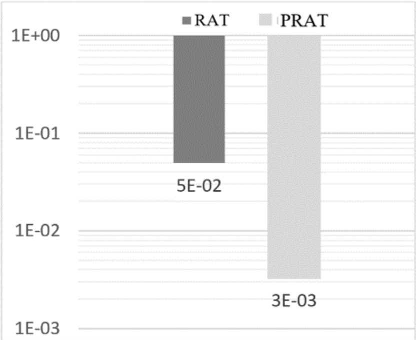
The results of the proposed RAT (pRAT) indicate an improvement over the previous version of the RAT, namely on the objectiveness of the DIAC, ease of use, interpretation and repeatability of the results obtained. An average score of 55 was obtained among the six MAWA representatives, for a baseline (correct evaluation) score of 60. Furthermore, it was found that the previous version of the RAT – presented in section 4 was too penalizing for the considered UAS, which resulted in a DIAC score of 20, cf. Figure 5-1, and estimation of mean time between failures (MTBF) of 40 flight hours – according to the probability of failure in Eq. (1).

Establishing a comparison between the RAT and pRAT for phases I and II, it becomes evident (Figure 5-1) that the introductions made in the pRAT clearly have a detrimental effect on the score of the DIAC. When comparing the estimated probability of failure from Eq. (1), the RAT score yields a probability (P_{cat}) of 5E-2 – 1 catastrophic failure per 20 flight hours – and the pRAT score predicts a probability of 3E-3, which corresponds to a failure rate of 1 per 333 flight hours.

Comparing these results with the flight statistics of the UAS used in the test scenario, it is possible to conclude that the estimated failure rate of the RAT is too conservative, given the experience of Portuguese Air Force with this system. Furthermore, feeding the previous P_{cat} in Eq. (7), and using a Risk Criticality Range of Medium (cf. Table 4-1), with a value of 5E-6 it is possible to determine that the maximum population density of the RAT and pRAT are 1.5 and 25 inhabitants per square kilometre. These results confirm the strictness of both frameworks, revealing that, according to the RAT it would only be possible to operate in deserted locations at the sea, while the pRAT suggests the UAS could be flown in locations with very low density population.



a) Scores at phase I and II.



b) Probability of catastrophic failure of the UAS.

Figure 5-1 – Comparison between RAT and pRAT.

Additionally, the current research pushed the application of the pRAT framework further to propose a reference model using the municipality population density of Portugal, using statistical demographic data, which is presented in Figure 5-2, where the vertical and horizontal axes of the chart are score and mass respectively. Here it is possible to see that low scores and higher masses impose severe limitations to the area of operation. This model aims at facilitating the interpretation of the required score of a UAS by a manufacturer or NAA evaluator.

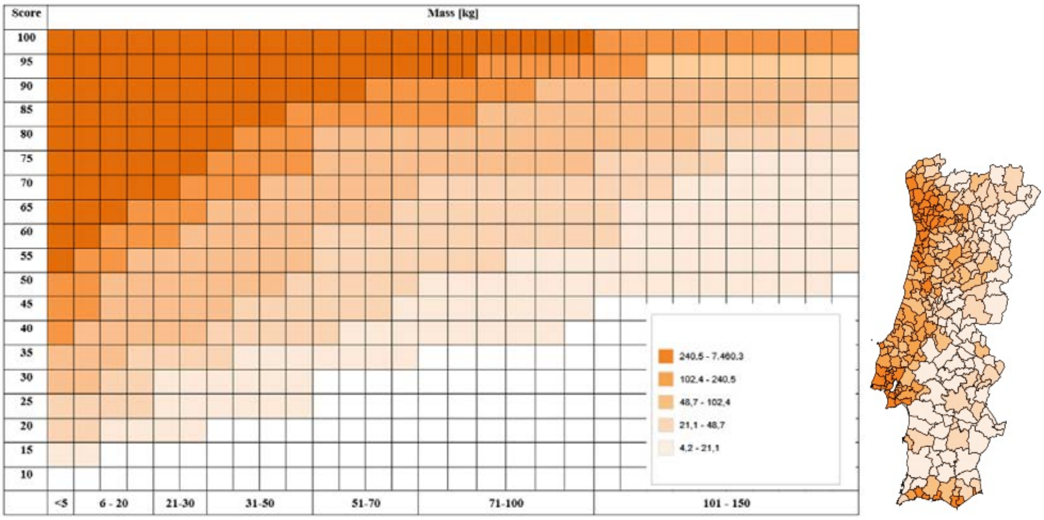


Figure 5-2 – Reference model for the score required to operate a UAS on a specific municipality in Portugal. Map adapted from [11].

6.0 COMPARISON OF DIFFERENT FRAMEWORKS

The present section focuses on summarily comparing the frameworks in the light factors considered to be of high importance. While SORA addresses the focuses on the analysis of the concept of operations, along with the ground and air risk classes and the correspondent specific assurance of integrity level, it does not address an equivalent level of safety of the UAS regarding its probability of catastrophic failure; nevertheless, this framework considers the ground and air risk of the operation, hence making it the most complete framework of the ones discussed in this article;

Conversely the FAA Order 8130.34D Risk Index aims at identifying the required certification tasks as function of risk assessment, based on the flight area, safety checklist and risk category. Such methodology is used to support the issuance of the special airworthiness certificates or special flights permits for R&D, crew training, market survey and production flight testing purposes.

In contrast with the aforementioned methodologies, the RAT framework estimates the probability of failure and consequent ground risk (R, Eq. (7)) using a design integrity checklist, which results in a score that is then converted to a probability of catastrophic failure and risk of hitting someone on the ground based on the population density. However, this methodology lacks on the assessment of operational and human factors, in particular in the assessment of human error, proven experience of the UAS operators and pilots with other systems. Furthermore, the RAT does not consider air-to-air risk collision probability nor collision avoidance, which, added to the lack of geofencing assessment make it more prone to errors in the estimation of the risk due to operational mishaps.

The pRAT gains from building on the strong points of the RAT, adding MoC and requirements to the DIAC criteria, which was implemented on a computational tool that automatically calculates the probability of catastrophic failure and ground risk from the answers of the users to predefined questions. It adds UAS characteristics to the score assessment and is considerably simpler than the RAT to use.

The previous statements, as a result of literature review, are summarised in Table 6-1, which is represented in the form of a spider chart for a simpler interpretation of the comparison in

Table 6-1 – Comparison of different frameworks

Factor Group	Description	Framework			
		SORA	Risk Index	RAT	pRAT
Intrinsic Factors (quality, safety)	Applicability (class or category)	Specific	R&D crew training, market survey production flight testing	*Open* and *Specific*	*Open* and *Specific*
	UAS characteristics	+++	++	+	+++
	Structural Integrity and Safety	++	+	+++	+++
	Software and System's Integrity	+	+	+++	+++
	Operational/testing flight time	+	-	+++	+++
	Life cycle estimation and support	++	++	+++	+++
	Probability of Catastrophic failure	++	++	++	+++
	Collision avoidance	+++	-	-	-
Human Factors	Operator Training and Qualifications	++	+	++	++
	Human Error	++	-	+	+
Operational Environment	Operations outside design standards	+++	+	++	++
	Probability of failure to operational reasons (weather, environment)	+++	+	+	++
	Infrastructure Damage estimation	++	+	-	-
	Populational density	++	+++	+++	+++
	Probability of causing death of people on the ground	+	+	+++	+++
	Probability of collision in flight	+++	++	-	-
	Geofencing	+++	-	-	-
Complexity[1]		+++	++	+++	++
Standardization Potential		+++	+++	+	++

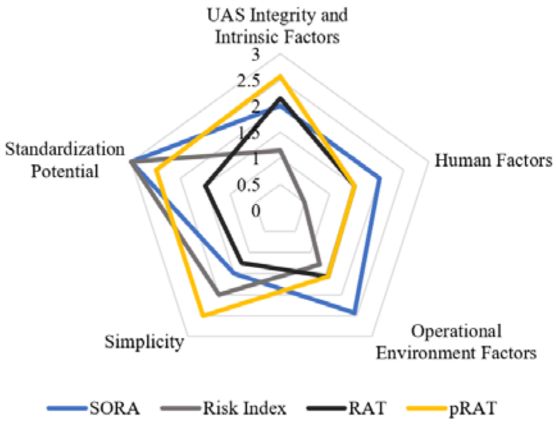


Figure 6-1: Comparison of Risk Assessment methodologies with respect to different factors.

[1] + low complexity; ++ medium complexity; +++ high complexity;

7.0 CONCLUSION

The airspace is an economic resource which is used by military and civil operators to fly manned and unmanned aircraft. As a result, the need for harmonization becomes important to assure that UAS are safe and that, respectively, are safely operated. Such methods can be new, a combination of the existing ones or just the acceptance of the existing methods without further assessment, namely for small UAS.

Standardization agreements (STANAG) 4702, 4703, and 4761 are often too demanding in terms of airworthiness requirements for airworthiness certification of UAS. As a result, risk-based assessment methodologies have been developed to assure an equivalent level of safety is achieved in UAS operations. In particular, the current most commonly accepted risk assessment frameworks are: a) the Guidelines on Specific Operations Risk Assessment (SORA), developed by the Joint Authorities for Rulemaking on Unmanned Systems (JARUS); b) the FAA Order 8130.34D Risk Index and c) the Risk Assessment Tool (RAT) developed within the European Defence Agency Remotely Piloted Aircraft Systems (RPAS) Airworthiness Regulatory Framework (ARF) Group.

It is concluded that SORA is a more holistic tool, comprising risk classes related to the likelihood of fatalities to third parties on ground and collisions in the air. Nevertheless, this framework does not address a comprehensive analysis of the design integrity of the platform, lacking in the intrinsic aspects of the UAS manufacturing. Conversely, the RAT reveals as the most demanding framework in terms of UAS safety levels, through the assessment of a design and integrity checklist, but fails to assess operational aspects such as operation scenarios and the probability of fatalities and risk resulting from air-to-air collision events.

The pRAT methodology builds on the RAT and further develops it by establishing means of compliance and criteria for the requirements of the design integrity checklist, which, added to the implementation of the framework in a computational tool make it a more intuitive methodology than the aforementioned ones.

FAA 8130.34D order points to the identification of certification tasks for UAS, through a risk assessment process that is based on the analysis of flight area, program letter and safety checklist, which are mitigated by the introduction of operational limitations. The identification of the applicable certification tasks derives from the risk group category. Despite simpler than the approaches identified before, this framework, gathers a considerable number of variables in risk group categories, which are based on size, mass, speed, flight history, altitude and operational parameters.

SORA and FAA Order 8130.34D Risk Index follow a step-by-step process to determine the operational safety objectives or the airworthiness certification tasks and appropriate limitations, respectively, whereas the RAT is based on a High Fidelity Risk Model. Despite these two different approaches, it is concluded that such risk assessment tools have a high potential for standardisation.

In order to conclude about standardisation or recognition of the abovementioned risk assessment for UAS, future work is needed, namely to include in the RAT the air risk model and a comparison between STANAGs, FAA Order 8130.34D Risk Index, SORA and RAT using the same UAS and Operational Scenarios.

ACKNOWLEDGMENTS

The authors would like to thank the members of the UAS Airworthiness Regulatory Framework Working Group (UAS ARF WG) of the European Defence Agency for the companionship, hard work and dedication to the development of the RAT framework.

Furthermore, the authors are thankful to the Portuguese Airworthiness Authority for the support and constant motivation in the study, development and implementation of risk assessment frameworks in Portugal.

To the Portuguese Air Force for allowing the present research to be conducted and presented.

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