ALARP and the Risk Management of Civil Unmanned Aircraft Systems

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Abstract

Key to the continued growth of the civil Unmanned Aircraft System (UAS) aviation sector is the development of a regulatory framework that will provide assurances in the management of the risks associated with their operation. Decisions in relation the evaluation and treatment of aviation risks need to be made in accordance with the As Low As Reasonably Practicable (ALARP) framework. There are a number of concerns in relation to the application of the ALARP framework to new technologies. This paper explores these concerns with respect to the risk management of civil UAS.

A review of the ALARP frameworks defined by the International Civil Aviation Organization (ICAO), the Civil Aviation Safety Authority (Australia), the Civil Aviation Authority (United Kingdom) and by the UK Health and Safety Executive is presented. This review identified subtle differences that can have a significant impact on how ALARP frameworks would be applied to UAS. A number of inconsistencies in the frameworks were also identified. These issues aside, it was found that a conceptual application of an ALARP framework can be made. However, significant difficulties were identified in the substantiation of a framework. In particular, the quantification of the decision criteria for UAS, the handling of uncertainty, and the identification, characterisation and representation of societal concerns within a framework. Guidance as to how the dimensions of societal concern and levels of risk can be jointly considered within an ALARP framework could not be identified within the literature. For new technologies such as UAS, these dimensions can be as significant a factor in decision-making as that of the quantified measures of the risk. Due to these deficiencies, there are significant difficulties in the application and substantiation of an ALARP framework to the risk management of new technologies such as UAS.

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1 Introduction

Much research is ongoing in the development of regulations to facilitate the safe, routine operation of UAS in civil airspace particularly over populated regions. In accordance with International Civil Aviation Organization (ICAO) Standards And Recommended PracticeS (SARPS), National Airworthiness Authority (NAA) policy, rule-making, and oversight activities should be governed by a systematic Safety Risk Management Process (SRMP) (ICAO 2009). A general description of the application of the SRMP to UAS can be found in Clothier & Walker (2013).

A number of frameworks can be used to support decision-making within the SRMP and in particular within the risk evaluation and treatment subprocesses. These decision-making frameworks include: As Low As Reasonably Practicable (ALARP), So Far As Is Reasonably Practicable (SFAIRP), As Low As Reasonably Achievable (ALARA), Globalement Au Moins Aussi Bon (GAMAB), Globalement Au Moins Equivalent (GAME), and Minimum Endogenous Mortality (MEM). Discussion on the differences between these decision-making frameworks can be found in Johansen (2009). ICAO SARPS stipulate that decision making within the SRMP should be made in accordance with the ALARP framework, Figure 1.

A review of the different specifications of the ALARP framework is provided in section §2. An essential component of the ALARP framework are the decision criteria that demarcate the different decision making regions. The definition of these decision criteria and discussion on the issues associated with their specification are presented in section §3. Decision making within the ALARP framework requires consideration of the level of risk and the degree of societal concern associated with the operation of UAS. The societal concerns associated with UAS operations and their representation in the ALARP framework are presented in section §4.

2 The ALARP Framework

The ALARP risk decision-making framework is intended to reflect the types of safety decisions made in everyday life (HSE 1992, 2001*b*). These decisions are based on the Level of Risk (LoR) and the degree of societal concern associated with the particular technology, activity or situation under assessment. From Figure 1, a particular situation can be classified as either:

1. Unacceptable, intolerable or broadly unacceptable (§2.1);
2. Tolerable or requiring review (§2.2);
3. Acceptable or broadly acceptable (§2.3); or
4. Negligible.

Central to the classes of *tolerable* and *acceptable* risks is the meaning of ALARP. This is discussed in Section §2.4. The varying definitions and conditions associated with each class are described in the following sub-sections.

2.1 Unacceptable, Intolerable or Broadly Unacceptable Risk

There are certain activities where people are unwilling to accept a risk regardless of the potential benefits. Situations of this nature have been referred to as unacceptable, intolerable or broadly unacceptable. In an effort to simplify terms, this paper will use the single term *unacceptable* in place of the various terms defined in the ALARP frameworks. This will maintain consistency with Figure 1 and reduce possible ambiguity.

ICAO describe an unacceptable LoR as "unacceptable under any circumstances, where the probability and/or severity of the consequences of the hazards are of such a magnitude, and the damaging potential of the hazard poses such a threat to the viability of the organization, that immediate mitigation action is required" (ICAO 2009). Civil Aviation Safety Authority (CASA) guidance material defines the concept of an unacceptable LoR as being unacceptable regardless of the benefits associated with the activity (CASA 2012).

The conditions associated with a situation deemed as having an unacceptable LoR can vary. Under the ICAO specification of the ALARP decision-making framework, an unacceptable risk must be reduced to a tolerable level or the activity cannot be undertaken. Similarly, the ALARP framework defined by CASA states that risk reduction measures "are essential regardless of cost" (CASA 2009). The CASA framework includes the additional statement that an activity assessed as having an unacceptable LoR may still continue but only where there exists "exceptional reasons" or "extraordinary circumstances". The concept of unacceptable LoR defined by the Health and Safety Executive (HSE) in the UK also includes the additional condition that activities may be allowed to continue if there are "exceptional reasons" (HSE 2001*b*). Definitions of an "exceptional reason" or an "extraordinary" or "extenuating" circumstance are not provided.

2.2 Tolerable Risk or Risks Requiring Review

For most activities stakeholders are willing to tolerate risk in return for certain benefits associated with the activity. These situations have been described as tolerable or those "requiring review". As per Figure 1 and in keeping with our endeavour to simplify terms, the term *tolerable* also refers to the concept of "requiring review" as defined in existing frameworks.

The Civil Aviation Authority (CAA) in the United Kingdom (UK) describe a LoR that requires review as being a LoR where the consequence and/or likelihood is of concern (CAA 2010*a*). CASA and HSE UK describe a tolerable risk as a risk that people are generally prepared to tolerate in order to secure benefits (CASA 2012, HSE 2001*b*). Within these frameworks, a tolerable risk is further described as a risk that 1) has been properly assessed and appropriate measures to control the risk have been implemented, 2) where the residual risk is not unacceptable and is considered to be ALARP, and 3) will be periodically reviewed (CASA 2009, 2012, HSE 2001*b*).

The CAA state that measures to mitigate a risk to ALARP should be sought for all risks belonging to the review class (CAA 2010*a*). Similar conditions are mandated for tolerable risks in the CASA and HSE frameworks. Under the ICAO ALARP framework, risks initially assessed as being tolerable do not require further mitigation provided mitigation strategies already in place guarantee that, to the foreseeable extent, the probability and/or severity of the consequences of hazards are kept under organizational control (ICAO 2009). An explicit definition of "organizational control" is not provided.

With the exception of the ICAO framework, all of the reviewed decision frameworks explicitly associate the concept of ALARP with the tolerable decision region. Within the ICAO Safety Management Manual, it is stated that safety risks must be managed to ALARP. However, an explicit association between this requirement and the concept of a tolerable risk is not made.[1]

For the CAA, CASA and HSE ALARP frameworks, the concept of a tolerable risk requires more than the demonstration that the risk is ALARP (e.g., it has also been correctly assessed and reviewed, etc.).

2.3 Acceptable or Broadly Acceptable Risk

Often many of the risks in daily life are accepted as insignificant or trivial, or are accepted because we have no practical control over them. Situations of this nature have been referred to as acceptable or broadly acceptable. In this paper the term *acceptable* also refers to the concept of broadly acceptable as defined in existing frameworks.

The CAA describe an acceptable risk as one where the occurrence of a "consequence is so unlikely or not severe enough to be of concern" (CAA 2010*a*). CASA and the HSE define the concept of acceptable risks as those situations where the risks are generally regarded as sufficiently low, insignificant, and adequately controlled (CASA 2009, 2012, HSE 2001*b*). ICAO describes acceptable risks as those that are acceptable as they currently stand (ICAO 2009).

Under the ICAO framework an activity initially assessed as having an acceptable LoR requires no action "to bring or keep the probability and/or severity of the consequences of hazards under organizational control" ICAO (2009). Whereas, under the CASA, HSE and CAA decision-making frameworks, the reduction of an identified risk to ALARP is not abandoned; individuals and organisations should continue

[1] A linkage between the concept of ALARP and tolerable risks is implied in a number of examples and illustrations throughout the document; see ICAO (2009).

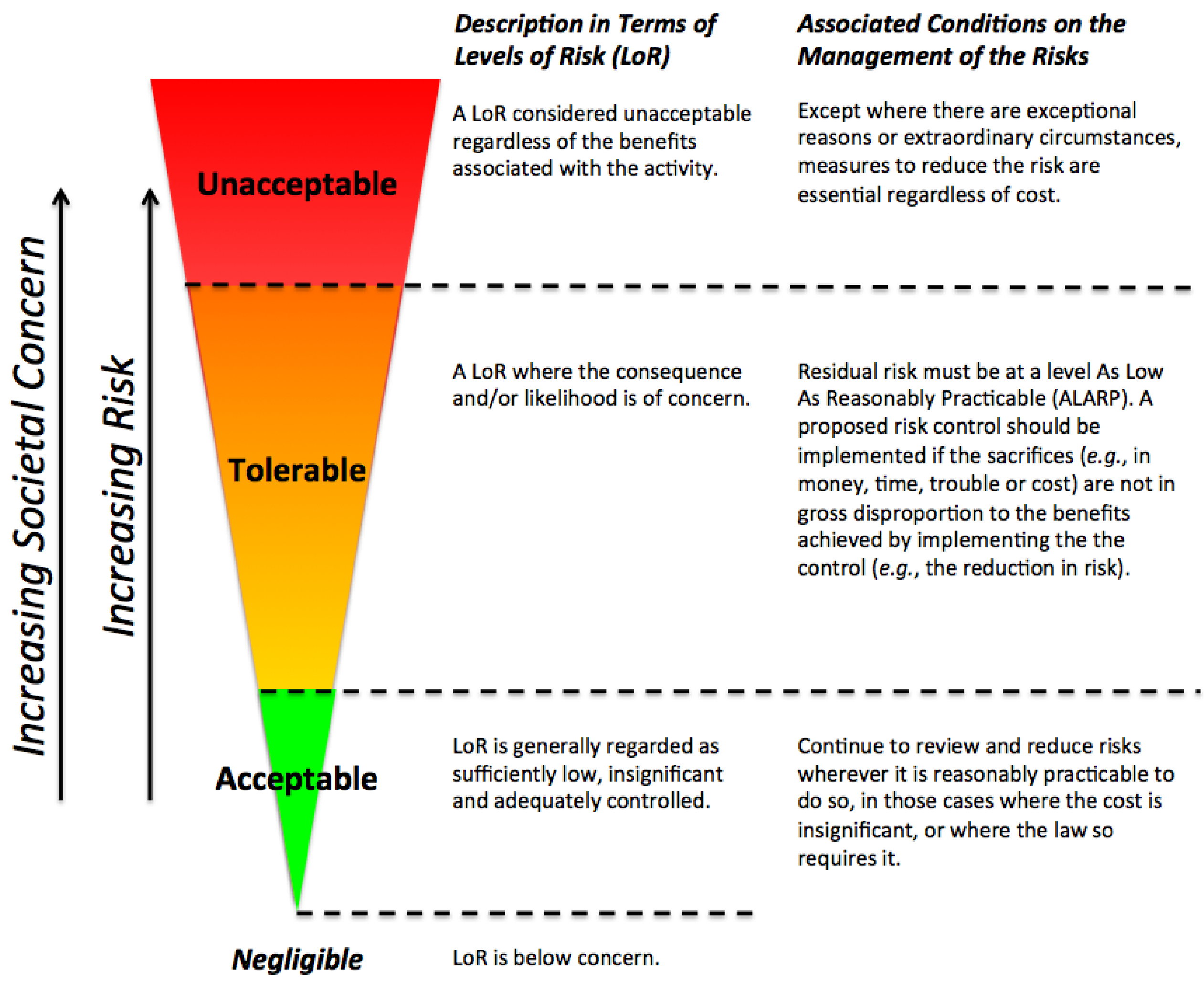

Figure 1: ALARP Risk Framework

to review and reduce risks wherever it is reasonably practicable to do so, in those cases where the cost is insignificant, or where the law so requires it (CAA 2010*b*, CASA 2009, HSE 2001*b*). This approach is consistent with the goal of continual safety improvement wherever practicable (CAA 2010*a*).

CASA states that detailed working necessary to demonstrate that risks are ALARP may not be required for those risks initially assessed as being acceptable (CASA 2012).

2.4 The Concept of ALARP

Central to the definition of the tolerable decision region is the concept of a risk being reduced to ALARP. But what does this mean? CASA and the CAA define the concept of ALARP as where the risk is low enough that attempting to make it lower, or the cost of assessing the improvement gained in an attempted risk reduction, would actually be more costly than any cost likely to come from the risk itself (CAA 2010*a*, CASA 2009). ICAO describes ALARP as the point where it can be shown that any further risk reduction is either impracticable or grossly outweighed by the cost, which requires consideration of the technical feasibility of further reducing the safety risk, and the cost (ICAO 2009).

CASA (2009) and the HSE (1992, 2001*b*) explicitly relate the concept of ALARP with the concept of a gross disproportionality. Specifically, ALARP is the point where "the cost of reducing the risk is grossly disproportionate to the benefit gained" (CASA 2009) and determining that risks have been reduced to a level as ALARP involves an assessment of the risk to be avoided, of the sacrifice or costs (e.g., in money, time and trouble) involved in taking measures to treat that risk, and a comparison of the two to see if there exists a gross disproportion (HSE 2001*b*). The meaning of gross disproportion is further discussed in the next Section §2.5.

2.5 Gross Disproportionality

CASA (2009) and HSE (2001*b*) explicitly relate the concept of ALARP with that of a gross disproportionality between the benefit and costs associated with assessing and implementing measures to further reduce the risk. A finding of gross disproportionality should be supported by a cost benefit analysis. Guidance on the analysis process and the meaning of gross disproportionality can be found in HSE (2001*a*), Jones-Lee & Aven (2011) and CASA (2010). It is important to note that a finding of gross disproportion, on its own, is not sufficient for a determination of ALARP.

Gross disproportion is typically not represented as a single value but a range of values expressed on a finite scale (or ranking), which increases as a function of increasing risk. The higher the LoR the higher the ratio of the cost to benefit that is needed to be considered in gross disproportion; see (HSE 1992, 2001*a*,*b*).

In the context of the safety risk management of civil aviation, a quantified specification of the ratio of costs to benefit sufficient to constitute gross disproportion could not be identified in the literature. Even if existing scales were available, they may not be appropriate for UAS due to differences in the nature of the costs and benefits that need to be evaluated (e.g., greater uncertainty in their estimation, and differences in visibility and equity of the distribution of benefit to people exposed to the risks). A quantified specification of the condition for gross disproportionality is not necessary to substantiate the ALARP framework. A determination of gross disproportion can be made qualitatively, thus avoiding the quagmire of social and political issues associated with placing a value on different loss outcomes (e.g., a cost per life saved).

2.6 Summary of Findings

The review has identified subtle differences between the various specifications of the ALARP decision-making frameworks available in the literature. These small differences can have a significant influence on the risk management of UAS operations. For example, in contrast to other specifications, the ICAO specification of the ALARP framework does not mandate that all tolerable risks be reduced to ALARP. Consequently, the LoR associated with an UAS operation can be considered *tolerable* within the ICAO ALARP framework but may not be *tolerable* within other frameworks. Differences in the associated conditions will also impact the setting of quantitative safety criteria within the framework. For example, the ICAO framework may set more stringent risk criteria to demarcate the region of *unacceptable risk* from *tolerable risk* to account for less stringent conditions on the management of the risks (e.g., not all tolerable risks need to be mitigated to ALARP). Further, National Airworthiness Authorities will need to determine a common set of high level safety goals within their respective State aviation safety programs. For example, the goal for continual safety improvement will influence the specification of the ALARP framework and its application to UAS.

A number of deficiencies were also identified. Key terms are undefined or only loosely defined. For example, the concepts of "organisational control" or "exceptional reason". There are also conceptual difficulties encountered in the different frameworks. Within the ICAO Safety Management Manual, it is stated that safety risks must be managed to ALARP. This statement conflicts with the definition of the decision classes of *intolerable* and *acceptable* defined within the ICAO ALARP framework. Further, mandating that all risks should be managed to ALARP conflicts with other requirements defined within the ICAO ALARP framework (e.g., conflict with the condition that risks initially assessed as being tolerable do not require further mitigation, described in section §2.2).

Irrespective of which ALARP framework is to be adopted, it is clear that the application of the ALARP framework in the risk management of UAS will require the assessment of more than the safety risks. Estimates of the benefit and cost associated with UAS operations as well as those associated with the risk management activity itself (e.g., the cost in time and money to conduct further assessment and evaluation) need to be made. For new technologies such as UAS this is very much a "chicken and egg" scenario, where knowledge of the true benefits and costs may not be entirely known *a priori* the operation. There can be as much uncertainty in the assessment of the benefits and costs as there is uncertainty in the assessment of the risks. Whilst there is much research being undertaken to understand and quantifiably characterise the safety risks associated with UAS technologies, very little is being undertaken to characterise the associated benefits and costs to society.

For some classes of UAS, the primary consideration may not be the safety risks associated with their operation. The quantified risk analysis conducted by Clothier et al. (2010), Magister (2010) and Fraser & Donnithorne-Tait (2011) show that for some types of UAS and for some UAS operations there is negligible risk to people and property. For such UAS and UAS operations the dominating factor driving risk reduction (a determination of ALARP) are the costs and associated benefits. It is important to note that the assessment of the benefit and cost to society requires more than an assessment of the economic values associated with the UAS operation (e.g., the economic loss due to destruction of the unmanned aircraft or damage to third party property). For example, society can place value on a wide range of tangible and intangible objects (e.g., reputation, trust in technology/brand). The gain (benefit) and the loss (cost) registered to these objects of value need to be considered in a determination of the ALARP. Finally, one should also consider the hypothetical and/or actual costs of *not* using the technology.

Like risk, there can be a difference between the cost/benefit assessed by an expert and the cost/benefit perceived by the different stakeholders. Whilst there is a wealth of literature exploring the issues associated with how stakeholders perceive risk, there is very limited research on the factors influencing stakeholder perception of costs and benefits within a safety decision making context. This leads to a plethora of questions, for example:

1. What benefits and costs associated with UAS operations should be considered?
2. Will these need to change for different classes of UAS or UAS operations? E.g., defence UAS operations versus civil UAS operations, small "harmless" UAS versus large UAS.
3. For whom should the benefits and costs be measured? The operator? A member of the public exposed to the risk? Society in general?
4. What factors influence stakeholder perception of the costs and benefits and how should they be accounted for in the ALARP framework? Will the concept of gross disproportion change for different stakeholders or situations where there a significant differences between assessments and stakeholder perception of the cost/benefit?

Assessments of the costs and benefits and a measure of the uncertainty associated with the assessment will be needed in order to apply the ALARP framework. Most disconcerting is that none of the existing specifications of the ALARP framework provide substantive guidance on the management of uncertainty (i.e., its identification, representation, and consideration in decision making). This is a significant issue for new technologies such as UAS where there is limited data and operational experience upon which to base assessments of the risk, cost and benefit. There are also uncertainties associated with the definition of the framework itself (e.g., the quantification of decision criteria within the framework).

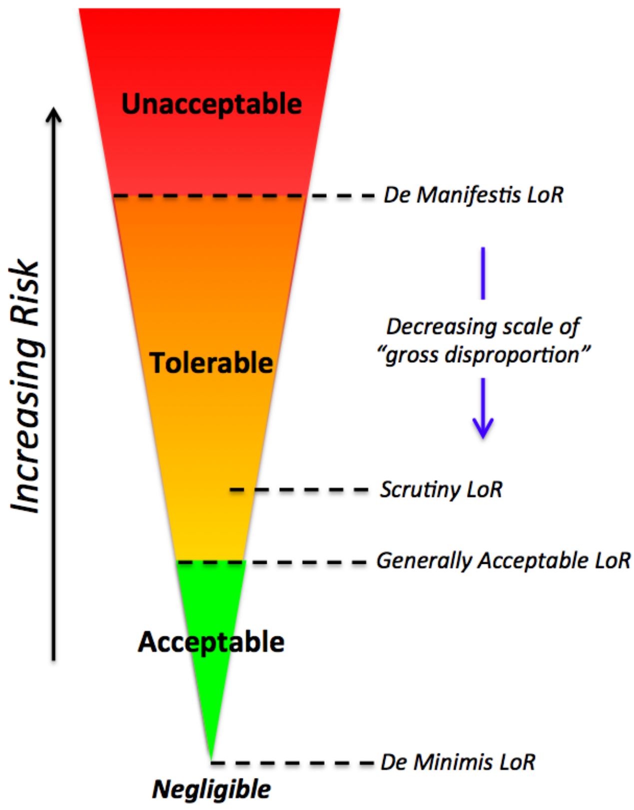

Figure 2: ALARP Risk Framework

3 Risk Criteria Within the ALARP Framework

High Level Safety Criteria (HLSC) governing the overall risk management and regulation of UAS operations have been defined. A detailed review of the different specifications can be found in Clothier & Walker (2013). An apparent consensus is that UAS, as a minimum, must demonstrate a level of safety equivalent to that of the safety performance currently demonstrated by Conventionally Piloted Aviation (CPA). This HLSC is commonly referred to as the Equivalent Level of Safety (ELoS) objective. In applying the ALARP framework to the safety risk management of UAS, a linkage between HLSC such as the ELoS objective needs to be established with the decision criteria defined within the ALARP framework.

The ELoS objective could be specified in relation to a number of decision criteria defined within the ALARP framework (Figure 2). These criteria include the *de manifestis*, *scrutiny*, *generally acceptable*, and *de minimis* criterion and the quantified concept of *gross disproportion*. In the next sections we explore the specification of the risk criteria within the ALARP framework. The specification of the *gross disproportion* criterion is the subject of a future research publication.

3.1 De Manifestis Risk Criteria

The concept of a *de manifestis LoR* stems from the legal definition of obvious risk and has been described as the LoR above which a person of ordinary level of intelligence intuitively recognises as being inherently unacceptable (Fulton 2002, RCC 2007). In the ALARP framework, the de manifestis LoR distinguishes an unacceptable LoR from a tolerable LoR (Figure 2).[2] It is important to note that demonstrating a LoR less than that of the de manifestis LoR is not sufficient for the risk to be deemed tolerable (refer to Section §2.2).

Except under extraordinary circumstances (refer to Section §2.1), de manifestis risk criteria can largely be considered as hard criteria (i.e., a rigid boundary on the decision space, one that must be satisfied). Therefore, de manifestis risk criteria essentially establish the minimum safety (or, equivalently, the maximum unsafe) expectation of civil UAS regardless of the potential benefit of the operation or whether the LoR can be practically achieved or not. One could logically conclude that the ELoS objective for UAS, which defines the overall *minimum* safety expectation for UAS operations, should be associated with de manifestis risk criteria within the ALARP framework. However, on deeper inspection, this association may not be appropriate.

Society tolerates the risk associated with CPA operations in return for the substantial and readily identifiable benefits of, for example, air transportation, aerial work and flying for recreation. However, society tolerates many activities with a higher LoR than that of passenger jet and turboprop fleet operations, which are referred to here as Conventional Airline CPA (CA-CPA). For example, it is widely recognised that passengers are more likely to die in a motor vehicle accident on their way to an airport than they are during their time on board a CA-CPA operation.

The level of Individual Risk (IR) of fatality associated with road accidents in the UK is estimated as 5.9×10^{-5} fatalities per member of the UK population per year (HSE 2001*b*). This LoR is two orders of magnitude greater than that associated with CA-CPA operations, which is estimated to be 2.3×10^{-7} fatalities per annum per worldwide population (Clothier et al. 2013). The point being made here is that society readily tolerates the risks associated with motor vehicles even though the LoR is greater than the LoR associated with CA-CPA transportation. It can be concluded that the LoR determined for CA-CPA operations does not reflect the critical LoR above which society broadly recognises as being unacceptable irrespective of its potential benefits (i.e., trade-offs between risk and benefit are still being made at a LoR two orders of magnitude greater than the LoR exhibited by CA-CPA operations). Further to this point, the HSE UK recommends a de manifestis IR of fatality of 1 in 1,000 per annum (1×10^{-3} per annum) for first parties and 1 in 10,000 per annum (1×10^{-4} per annum) for third parties (HSE 1992, 2001*b*). It is observed that these specifications of de manifestis criteria are more than two to three orders of magnitude greater than measures of risk determined for current worldwide CA-CPA operations.

The examples above indicate that society is willing to make a trade-off between the benefit, cost and risk for activities with a higher LoR than that currently exhibited by CA-CPA operations. The specification of the de manifestis HLSC for UAS should permit similar trade-offs to be made for UAS for a comparable or higher LoR.

Associating the ELoS objective with de manifestis criteria within the ALARP framework would be inconsistent with the fundamental decision scenario that de manifestis criteria are meant to reflect (i.e., a demarcation between those situations where costs and benefits are not factored into the safety decision making process). Further, such an association would

[2] Within the CASA framework, de manifestis criteria are indirectly referred to as basic safety limits (CASA 2009).

establish a minimum LoR requirement on UAS operations that is orders of magnitude above LoR already tolerated by society for other activities (including, for example, sport aviation operations or road transportation).

A more appropriate basis for specifying the de manifestis LoR for UAS are existing published regulatory limits or LoR determined from studies characterising the *upper limit* of public acceptability of manmade risks (e.g., CPA, power generation, etc.).

3.2 Generally Acceptable Risk Criteria

Unlike *de manifestis LoR* criteria, *generally acceptable LoR* criteria represent goal LoR. They are soft requirements that should be satisfied taking into consideration hard practical constraints on the available technology, on its operation and on the resources available to mitigate the risks.[3]

HSE guidelines suggest that the generally acceptable risk criteria should represent LoR comparable or lower than the background LoR members of the public are readily exposed to in day-to-day life (e.g., to annual risk of death due to a lightning strike). The HSE recommends the generally acceptable individual risk of fatality criterion of one in a million per annum (1×10^{-6} per annum) (HSE 2001*b*), stating that this LoR is extremely small compared to the typical background risk of fatality of one in a hundred per annum (1×10^{-2} per annum) averaged over a lifetime (HSE 2001*b*). There are a number of social and psychological factors that need to be taken into consideration when making a comparison between the risks associated with a technology (such as UAS) and the risks society readily accepts as an inescapable part of life. The key difference being that exposure to a technology is controllable. This difference and other social and psychological factors are discussed in Section §4.

An alternate approach for specifying generally acceptable risk criteria is through reference to LoR currently accepted in society for a similar technology or industry. In the context of UAS, the generally acceptable LoR could be specified in terms of the current LoR for CPA operations. The CPA LoR can vary significantly depending on the historical period of assessment and the type of CPA operation (Clothier & Walker 2006). For example, the measures of individual fatality risk due to a midair collision determined by Fulton et al. (2009) clearly show the variation between the LoR for the aviation sectors of general aviation, sport, regular passenger transport aviation. This variation in LoR also illustrates differences in society's appetite for risk and the different risk-cost-benefit-feasibility trade-offs that exist for different sectors of the CPA industry (e.g., acceptability of risks associated with sport aviation versus those associated with regular public transportation).

Society is becoming increasingly risk aware (Slovic 1987, Kates & Kasperson 1983, Slovic 1999). Further, the public believe they are exposed to more risks today than they were in the past and that these risks will continue to increase (Slovic 1999). With this increasing awareness comes increasing opposition to new sources of risk (Slovic 1999), particularly those associated with new technologies (Kates & Kasperson 1983). In addition, there is the increasing expectation for assurances in the safety of systems that were previously considered as of lower societal concern. This shifting social climate is a challenging environment for both the proponents of new technologies and the authorities charged with their regulation.

Therefore, when considering historical CPA LoR it is critical to understand that those LoR may only have been acceptable only in that period and would be considered very differently today. The acceptable LoR for aviation that bracketed the start of CPA at Kitty Hawk was higher than the acceptable LoR that existed for the USA space program, which is different to the acceptable LoR for today's regular public transportation and general aviation sectors. An argument that UAS as a new technology should be afforded a grace period with LoR similar to that of the early CPA era would not be accepted. Society has evolved generally acceptable risk criteria across the aviation sector that are independent of new technology introductions.

Finally, one must also note the difference between a goal LoR (i.e., what is aspired to or designed for) and the actual safety performance demonstrated by a system. A LoR based on historical CPA accident and incident data reflects the latter of these measures and not the goal safety performance for CPA. The demonstrated safety performance of CPA may far exceed or fall short of the goal LoR for CPA (i.e., a LoR deemed generally acceptable for the CPA). CPA accident and incident data may not provide a suitable basis for defining the *goal* LoR (i.e., the generally acceptable LoR) for UAS within an ALARP framework. It is more appropriate to specify generally acceptable risk criteria for UAS in relation to other criteria reflecting *goal* LoR. For example, it would be more appropriate to specify generally acceptable risk criteria for UAS through reference to the generally acceptable LoR (a goal LoR) used within an ALARP framework for a CPA category. If such criteria were not available, generally acceptable LoR as specified in the ALARP frameworks for other socio-technical risks could be used.

3.3 De Minimis Risk Criteria

The *de minimis LoR* stems from the legal principle de minimis non curat lex: "the law does not concern itself with trifles" (Fulton 2002, RCC 2007, Pate-Cornell 1994). The de minimis LoR can be used within the ALARP framework as a guide for determining when risks have been managed to a level that could be considered below general concern, i.e., that a LoR is approaching negligible risk. Like the generally acceptable LoR, the de minimis LoR is a goal LoR. The HSE UK proposes a de minimis risk of individual fatality of one in ten million per annum (1×10^{-7} fatalities per annum) (HSE 2001*b*).

In accordance with the CASA, HSE and CAA-UK ALARP frameworks, the requirement to continue to reduce the risks applies regardless of whether the LoR is considered generally acceptable or not. This is consistent with the overarching goal to continually pursue safety improvement in civil aviation. Therefore, it is not mandatory that de minimis risk criteria be defined in the ALARP framework for UAS as mechanisms to reduce risk should always be undertaken until a gross disproportion can be demonstrated.

3.4 Scrutiny Risk Criteria

A reference or scrutiny level is sometimes used to put newly assessed risks in context with risks that have been tolerated or broadly accepted in the past (Clothier & Walker 2013). Scrutiny LoR are not decision criteria but points of reference that allow deci-

[3] Within the CASA framework, the generally acceptable LoR is indirectly referred to as the basic safety objective (CASA 2009).

sion makers to contrast newly assessed risks against the management of similar or familiar risks. Scrutiny lines can exist anywhere in the tolerable or acceptable regions of the ALARP framework and are often specified in terms of LoR determined for a similar activity or industry.

The current levels of risk exhibited by CPA provide a good reference point against which to contrast the safety performance of civil UAS. UAS are a viable alternative to CPA in many applications. Such alternatives should be evaluated in accordance with the general principles of ALARP. Further, the media and members of the public are likely to use the current safety performance of CPA as a "litmus test" for UAS (Clothier & Walker 2013), thus a reference LoR may be a useful tool in communicating the risks to different stakeholder groups. For these reasons it is recommended that the ELoS objective be represented as scrutiny criteria within the ALARP decision making framework.

3.5 Impact of Risk Exposure

The preceding discussion on risk criteria has assumed an equal risk exposure level when comparing different criteria. This is a natural tendency resulting from biases such as "worst case thinking" and "availability heuristic" (Evans 2012), where risk is assessed from a perspective that the worst outcome will be more likely and that our measure of risk is biased by recalling recent similar experiences. The applicability of CPA risk thresholds to UAS may be an obvious social starting point, but a deeper assessment would reveal that the exposure of people and property is very much dependent on the specific mission. This point is clearly illustrated in the quantitative risk analyses conducted by Weibel (2005), Clothier & Walker (2006), Clothier et al. (2007), and Dalamagkidis et al. (2009), amongst others. For CPA, the same variability in exposure is not encountered as there is always at least one person exposed to the primary hazards (i.e., the pilot). Different criteria may need to be substantiated within ALARP framework for UAS.

3.6 Summary

The review of risk criteria within the context of the ALARP framework has identified that concepts such as *de manifestis LoR*, *generally acceptable LoR*, and *de minimis LoR* would adequately define the divides between unacceptable, tolerable, and acceptable risk classifications. However, moving beyond the conceptual application of the ALARP framework to UAS, reveals many complications in the actual specification of these criteria. This complexity is driven by the variability of risk tolerance in society both in time and via the inherent cost/benefit analysis undertaken for each hazard. This is further complicated when taking into account the impact of risk exposure, which indicates that the criteria are not static and that direct comparisons between particular CPA categories and UAS may not be appropriate.

4 Representing Societal Concern

Discussion thus far has focussed on the decision dimension of risk. As illustrated in Figure 1, the ALARP decision-making framework has an additional dimension describing societal concern. The dimension of societal concern reflects the degree of "socio-political response" (HSE 2001*b*) to the realisation of an hazard. It has been stated that the origin for societal concern is public aversion to certain characteristics of the hazards concerned (HSE 2001*a*). Some characteristic features attracting a higher degree of societal concern include:

1. Lack of familiarity of the hazardous activity/technology
2. Scale of the detrimental outcomes (e.g., multiple fatalities or widespread detriment)
3. Prolonged effects
4. Vulnerability of the people impacted by the hazard (e.g., children and the elderly)
5. Lack of equity of the distribution of risks or benefits associated in the activity
6. Involuntariness of exposure
7. Inspiration of dread

(HSE 2001*a*)

With the exception of the above, the existing literature provides very little guidance on how these characteristic 'features' can be measured or on how they can be incorporated into the ALARP framework (e.g., as criteria to be balanced alongside measures of risk). General guidance on the consideration of the dimension of societal concern specific to the safety risk management of civil aviation could not be identified in the literature. The following sections provide a brief exploration of these factors in the context of UAS.

4.1 Representing Societal Concern Due to Scale of Detrimental Outcomes

Societal concerns arising due to the occurrence of multiple fatalities in a single event can be characterised through a measure of the Societal Risk (SR). The representation of the ALARP framework using SR measures is provided in Figure 3. Horn et al. (2008) discussed some of the mathematical foundations of SR.

As illustrated in Figure 3, the risk decision criteria (e.g., de minimis, de manifestis criteria) are not represented as a single value but a function of the potential magnitude of loss for a single event. The barrier functions are monotonically-decreasing, reflecting society's apparent aversion towards those accidents with the potential for greater levels of harm (although there is some debate as to whether it is controllability or voluntariness that is causal for this difference in tolerability; see (Reid 2000)).

Society's perception of a LoR is largely driven by the nature and magnitude of the potential consequences, more so than the associated likelihoods of occurrence. Society tends to be more adverse towards those potential accidents that have a higher degree of loss. The magnitude of the potential loss primarily depends on the nature of the exposure relationship between the hazard and the population of people at risk. For example, accidents involving small general aviation aircraft tend to result in a smaller number of fatalities than those accidents involving commercial passenger aircraft operations. This is because a smaller number of people are exposed given the occurrence of the hazard. Measures of SR provide an important tool for accounting for differences in the "risk portfolio" within an industry or aggregation of activities (Horn et al. 2008).

Safety criteria expressed in terms of SR are widely used in the regulation of a diverse range of industries

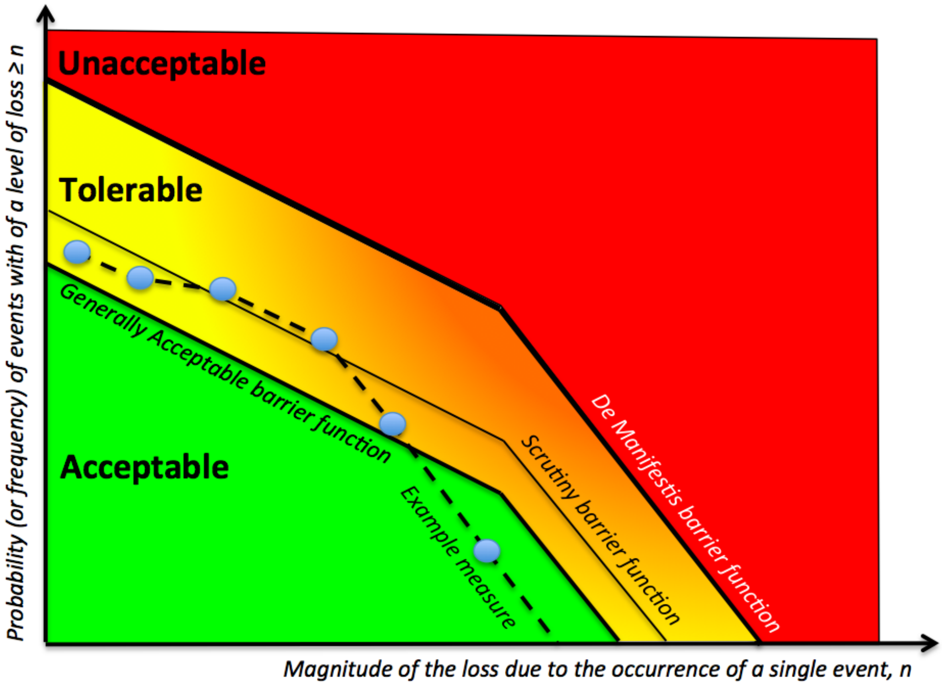

Figure 3: ALARP Risk Framework Represented Using Measures of Societal Risk

(a review on the use of SR in the European Union for a range of industries can be found in Trbojevic (2005)). The HSE states that the "proper regulation of risks requires that both the individual risks and societal concerns engendered by a hazard must be addressed" (HSE 2001*b*).

The risk profile associated with UAS operations will be different to that associated with CPA. There are significant differences between the CPA and UAS fleets (Palmer & Clothier 2013). In particular, the significant diversity in the UAS fleet compared to that of the CPA fleet. Due to this diversity, the risk profile associated with the UAS fleet is likely to be very different from that of the CPA fleet. For example, almost 70% of the current UAS fleet have a maximum take-off mass of less than 150 kg (Palmer & Clothier 2013). Subsequently, the risk profile for the UAS fleet for the impact of ground collision is most likely to be characterised by accidents involving a smaller number of casualties. The SR profile associated with the hazard of a midair collision involving UAS will also be different to that of CPA. This is largely due to the absence of a population of people onboard the unmanned aircraft who would be exposed to the hazard of a midair collision. For these reasons, measures of the SR based on CPA accident and incident data should only be used to define scrutiny barrier functions within ALARP framework for UAS (e.g., for use as guidance only). Due to differences between classes within the UAS and CPA fleets (Palmer & Clothier 2013), the scrutiny barrier function for UAS should be based on a fleet-level aggregation of the safety performance of CPA.

4.2 Representation of Other Aspects of Societal Concern

Measures of SR do not provide a comprehensive representation of the dimension of societal concern. Other factors influencing societal concern, as mentioned in §4, are not taken into account (e.g., familiarity, dread, vulnerability, etc.) by measures of SR.

Some aspects are indirectly captured within the existing safety risk management framework. The aspects of controllability of exposure, voluntary and involuntary exposure, and the distribution of benefits to those exposed are indirectly taken into account when making the distinction between the risks posed to first, second and third parties. More stringent safety criteria are typically imposed for those hazards that pose a risk to people whom have limited controllability over their own exposure to the hazard, are involuntarily exposed, or to those who receive no immediate or readily perceived benefit from the hazardous activity.

The HSE makes the distinction between workers (first parties) and members of the public (third parties), proposing different safety criteria for each as summarised in Table 1. Similar distinctions are made in the management of safety on defence ranges in the USA (RCC 2007). In the context of UAS operations, first parties can be identified as those people directly associated with the operation of the unmanned aircraft, i.e., remote pilots and field personnel. Third parties are those people over flown by the UAS who have no direct connection to the UAS operation (e.g., members of the public). In the Common Risk Management Framework for Airspace and Air Traffic Management in Australia (DOIT 2012) it is stated that "safety criteria must be premised on the basis of the effect on aircrew, other safety critical staff, the travelling public and the community". As evident in this statement, there is the additional category of people at risk that must be considered in the risk management of aviation hazards, secondary parties. In the context of UAS, secondary parties would be those who are somehow involved or receive benefit through aviation operations but are not directly associated with the operation the UAS. An example of secondary parties would be pilots, crew and passengers on board other aircraft who accept some level of risk in return for certain benefits (e.g., employment, transportation, etc.).

It is important to note that for UAS, the primary risks are to second and third parties, whereas for CPA the primary risks are to first and second parties (Clothier & Walker 2013). The difference in the populations at risk must be taken into consideration when specifying safety criteria for UAS. For example, it would be inappropriate to use existing safety criteria defined for risks to CPA first parties as a basis for defining safety criteria for UAS.

An accident can have an impact beyond that of injury to people. Some of these broader losses are indirectly captured in the assessment of the costs as part of the cost-benefit analysis undertaken for a determination of gross disproportion. Specifically, ICAO states that the following cost factors should be considered as part of the cost-benefit-analysis process: loss of business, equipment, productivity, managerial, legal, cultural, market, political and public (ICAO 2009). For UAS, loss of the unmanned aircraft, damage to the environment or property, the loss in earnings and loss of public or client confidence may be particularly significant for smaller UAS where the LoR to people is low. Such aspects would be considered as a secondary concern in the risk management of CPA. The potential impact on the efficiency of the existing airspace system is also important consideration.

It is important to note that the scope and magnitude of loss associated with an UAS accident, particularly in the early phases of their operation, can be amplified. The concept of the social amplification of risk is described in Kasperson et al. (1993).

4.3 Differences in Social Concern between Manned and Unmanned Aviation

There will be differences in stakeholder perceptions of the risks associated with the operation of UAS compared to that of CPA. This will in turn affect the acceptability/tolerability of the risks and consequently, the specification of safety criteria for UAS within the ALARP framework. Clothier & Walker (2013) describe a number of factors that may lead to differences in the perception and in turn acceptability of UAS operations compared to that of CPA operations. These factors include the visibility of the benefits, voluntariness, control, and the knowledge and information available to stakeholders. Other general factors that can influence public perception of risks are described in Slovic (1987). Directly adopting existing risk criteria (e.g., generally acceptable criteria) for CPA may not reflect differences in stakeholder perceptions and preferences in relation to the risks associated with UAS technologies.

As discussed previously, it is important to note that stakeholder perception and preferences towards UAS technologies will also change with time. It is likely that stakeholders will have a heightened sensitivity towards the risks while UAS remain a new and unfamiliar technology. This is a common situation for new technologies, as described by Melchers (2001):

> *History suggests that a new technology will only survive if it has no major catastrophes early in its development.*

Community attitudes towards the safety of UAS technologies are likely to change as stakeholders become more accustomed with the technology, more familiar with its associated risks and benefits, and as more information becomes available to regulators (i.e., trust). Further, the nature of the risks associated with the UAS industry will change as the sector grows and as new applications for the technology are identified and exploited.

The specification of safety criteria for UAS will need to reflect the initial sensitivity of stakeholders to new and unfamiliar technologies and the changing nature of the risks presented by UAS. Safety criteria will also need to reflect the objective for continued safety improvement as stipulated in the ICAO States' Safety Plan (SSP) (ICAO 2009). It can be concluded that the substantiation of the ALARP framework for UAS will need to be periodically revised to account for differences in stakeholder perceptions and preferences, changes in the risk profile associated with UAS operations, and to satisfy the objective for continued safety improvement as defined in the SSP.

Finally, different stakeholders will have different concerns. It cannot be assumed that the set of safety criteria defined in the ALARP framework are necessarily representative of all stakeholder perspectives.

4.4 Summary of Societal Concern

This section has only briefly touched on the dimension of societal concern within the ALARP framework. The most significant finding of this review is that the literature provides very little guidance as to this dimension and its incorporation into the ALARP framework.

With the exception of some high level discussion presented in Clothier & Walker (2013), no existing literature could be identified which specifically addressed the impact of societal concerns on the safety risk management and in turn regulation of UAS technologies. Addressing societal concerns will be a significant factor in the safety risk management and decision making for UAS, particularly in the early phases of the introduction of the technology. A number of factors influencing societal concern have already been identified but there is almost no guidance as to how these factors can be taken into consideration in the ALARP framework. Measures of SR and accounting for differences in the voluntariness of the exposure do not account for all of these factors. Further research to identify, characterise and incorporate societal concerns in the risk management of UAS is needed.

5 Conclusions

This paper has set out to identify and explore the issues of applying the As Low As Reasonably Practicable (ALARP) decision-making framework to the risk management of UAS. It was found that there are subtle differences between the different specifications of the ALARP framework made in safety literature. Inconsistencies in the existing frameworks were also identified. These subtle differences and inconsistencies can have significant impact on how the ALARP frameworks are to be substantiated for the risk management of UAS. A single, consolidated framework, should be adopted by the aviation safety community.

A conceptual application of the ALARP framework can be made using *de manifestis LoR*, *generally acceptable LoR*, and *de minimis LoR* as the boundary definitions between *Unacceptable*, *Tolerable*, *Acceptable*, and *Negligible*. However, significant difficulties were identified in the substantiation of the ALARP framework. In particular, in the specification of the ALARP decision criteria and the identification, characterisation, and representation of societal concerns.

Difficulties in relation to the specification of the ALARP decision criteria arise due to a number of factors, including:

1. Differences in the primary populations at risk, which in turn creates a difference in the nature of the exposure and the acceptability of the risks.

Decision Criteria	Population	Individual Risk of Fatality per Annum
De manifestis	Workers	1×10^{-3}
De manifestis	Members of the public	1×10^{-4}
Broadly acceptable	Workers and members of the public	1×10^{-6}

Table 1: Individual Risk (IR) of fatality criteria for different populations at risk (HSE 2001*b*)

2. Unique systems and missions for which there are no CPA equivalents.
3. Differences in how society perceives the risks and benefits associated with new technologies such as UAS compared to that for established and familiar technology such as CPA. This in turn influences society's appetite for risk.
4. The time sensitivity of the acceptability of the risks associated with new technologies.
5. Additional uncertainties that need to be incorporated in the cost benefit analysis for UAS (to support a finding of gross disproportion)

Guidance as to how the dimensions of societal concern and levels of risk can be jointly considered within the ALARP framework could not be identified in the literature. In the case of new technologies, such as UAS, the dimension of societal concern can be as significant a factor in decision making as that of the quantified measures of the risk. Further research on the impact of social dimensions on risk thresholds, beyond the quantification of risk, is required. Decision making requires not only an appreciation of the risk but how individuals and society respond to that risk.

Finally, none of the existing specifications of the ALARP framework provide substantive guidance on the management of uncertainty. This is a significant issue for new technologies such as UAS where there is limited data and operational experience upon which to base assessments of the risk, cost and benefit.

In considering these deficiencies it is concluded that there are significant difficulties in the application and substantiation of the ALARP framework to the risk management of new technologies such as UAS.

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References

CAA (2010*a*), CAP760 guidance on the conduct of hazard identification, risk assessment and the production of safety cases. for aerodrome operators and air traffic service providers., Technical report, Safety Regulation Group, Civil Aviation Authority, Norwich, United Kingdom.

CAA (2010*b*), Safety management systems - guidance to organisations, Technical report, Civil Aviation Authority, London, UK.

CASA (2009), CAAP SMS-1(0) safety management systems for regular public transport operations, civil aviation advisory publication, Technical report, Civil Aviation Safety Authority, Canberra, Australia.

CASA (2010), Cost benefit analysis procedures manual, Technical report, Civil Aviation Safety Authority, Canberra, Australia.

CASA (2012), Booklet three - safety risk management. SMS for aviation–a practical guide, safety management systems (SMS) resource kit., Technical report, Civil Aviation Safety Authority, Canberra, Australia.

Clothier, R. A., Lin, X. & Fulton, N. L. (2013), Quantification of high level safety objectives for civil unmanned aircraft systems, Technical Report EP13967, Division of Mathematics, Informatics and Statistics, Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Clothier, R. A., Palmer, J. L., Walker, R. A. & Fulton, N. L. (2010), Definition of airworthiness categories for civil unmanned aircraft systems (UAS), *in* '27th Congress of the International Council of the Aeronautical Sciences (ICAS 2010)', Nice, France.

Clothier, R. A. & Walker, R. A. (2006), Determination and evaluation of UAV safety objectives, *in* '21st International Unmanned Air Vehicle Systems Conference', Bristol, UK.

Clothier, R. A. & Walker, R. A. (2013), *Safety Risk Management of Unmanned Aircraft*, Springer Science and Business Media B.V., Dordrecht, Netherlands.

Clothier, R. A., Walker, R. A., Fulton, N. L. & Campbell, D. A. (2007), A casualty risk analysis for unmanned aerial system (UAS) operations over inhabited areas, *in* 'Twelfth Australian International Aerospace Congress Conference, 2nd Australasian Unmanned Air Vehicles Conference', Melbourne, Australia.

Dalamagkidis, K., Valavanis, K. & Piegl, L. (2009), *On Integrating Unmanned Aircraft Systems into the National Airspace System. Issues, Challenges, Operational Restrictions, Certification, and Recommendations*, Vol. 36 of *International Series on Intelligent Systems, Control, and Automation: Science and Engineering*, Springer Science and Business Media B.V.

DOIT (2012), Common risk management framework for airspace and air traffic management, Technical report, Department of Infrastructure and Transport Department of Defence, Civil Aviation Safety Authority, Airservices Australia, Canberra, Australia.

Evans, D. (2012), *Risk Intelligence: How to Live With Uncertainty*, Atlantic Books.

Fraser, C. S. R. & Donnithorne-Tait, D. (2011), An approach to the classification of unmanned aircraft, *in* 'Proceedings of the 26th International Conference on Unmanned Aerial Vehicle Systems (UAVS) 2011', Curran Associates, Red Hook, USA, pp. 157–211.

Fulton, N. L. (2002), Regional airspace design: A structured systems engineering approach, PhD thesis, School of Aerospace and Mechanical Engineering, the University of New South Wales, Canberra, Australia.

Fulton, N. L., Westcott, M. & Emery, S. (2009), 'Decision support for risk assessment of midair collisions via population-based measures', *Transportation Research Part A: Policy and Practice* **43**(2), 150–169.

Horn, M. E., Fulton, N. & Westcott, M. (2008), 'Measures of societal risk and their potential use in civil aviation', *Risk Analysis* **28**(6), 1711–1726.

HSE (1992), The tolerability of risk from nuclear power stations, Technical report, Health and Safety Executive (HSE).

HSE (2001*a*), 'Principles and guidelines to assist HSE in its judgements that duty-holders have reduced risk as low as reasonably practicable'.
URL: *http://www.hse.gov.uk/risk/theory/alarp1.htm*

HSE (2001*b*), Reducing risks, protecting people. HSE's decision-making process, Technical report, Health and Safety Executive, Norwich, United Kingdom.

ICAO (2009), Safety management manual (SMM), doc 9859, Technical report, International Civil Aviation Organization (ICAO), Montréal, Canada.

Johansen, I. L. (2009), Foundations and fallacies of risk acceptance criteria, Technical Report ROSS (NTNU) 201001, Norwegian University of Science and Technology, Trondheim, Norway.

Jones-Lee, M. & Aven, T. (2011), 'ALARP—what does it really mean?', *Reliability Engineering & System Safety* **96**(8), 877–882.

Kasperson, R. E., Renn, O., Slovic, P., Brown, H., Emel, J., Goble, R., Kasperson, J. X. & Ratick, S. (1993), 'The social amplification of risk: A conceptual framework', *Risk Analysis* **8**(2), 177–187.

Kates, R. & Kasperson, J. (1983), Comparative risk analysis of technological hazards, *in* 'Proceedings of the National Academy of Sciences of the United States of America', Vol. 80, pp. 7027–7038.

Magister, T. (2010), 'The small unmanned aircraft blunt criterion based injury potential estimation', *Safety Science* **48**(10), 1313–1320.

Melchers, R. E. (2001), 'On the ALARP approach to risk management', *Reliability Engineering and System Safety* **71**(2), 201–208.

Palmer, J. L. & Clothier, R. A. (2013), Analysis of the applicability of existing airworthiness classification schemes to the unmanned aircraft fleet, *in* '15th Australian International Aerospace Congress (AIAC 15)', Melbourne, Australia.

Pate-Cornell, E. (1994), 'Quantitative safety goals for risk management of industrial facilities', *Structural Safety* **13**(3), 145–157.

RCC (2007), Standard 321-07: Common risk criteria for national test ranges, Technical report, Safety Group Risk Committee, Range Commanders Council, US Army White Sands Missile Range, New Mexico.

Reid, S. G. (2000), 'Acceptable risk criteria', *Progress in Structural Engineering and Materials* **2**(2), 254–262.

Slovic, P. (1987), 'Perception of risk', *Science* **236**(4799), 280–285.

Slovic, P. (1999), 'Trust, emotion, sex, politics, and science: Surveying the risk-assessment battlefield', *Risk Analysis* **19**(4), 689–701.

Trbojevic, V. M. (2005), Risk criteria in EU, *in* 'European Safety and Reliability Conference ESREL', European Safety and Reliability Association, Tri City, Poland.

Weibel, R. E. (2005), Safety considerations for operation of different classes of unmanned aerial vehicles in the national airspace system, Masters thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, USA.