Report

Research Programme on Collisions with Drones: Work Areas 2-5 Final Report

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Administration Page

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A	13th April	Early draft for review by EASA
1	21st July	First issue
2	31st August	Second issue, with requested clarifications

Executive Summary

In 2016, the European Aviation Safety Agency (EASA) assembled a 'Drone Collision' Task Force in response to the increasing perceived risk of collision between Unmanned Air Systems (UAS) and manned aircraft. The Task Force published its assessment of the threat [1] in October 2016, which included three key recommendations for further research and risk assessment.

To further this study, EASA tendered a proposal [2] with the aim to establish the baseline for subsequent coordinated and collaborative research, accounting for existing research which could be extended to satisfy the Task Force recommendations. The tender defined five Work Areas (WA) to be considered:

- WA1: **Proposed Research Programme**, drawing from recommendations of subsequent WA2-WA5;
- WA2: **Refinement of UAS threat**, maturing the definition of the UAS threat and identifying a route to develop numerical representations.
- WA3: **Impact Effect Assessment**, identifying locations at which impacts might occur for the various different classes of manned aircraft.
- WA4: **Hazard Effect Classification**, outlining an approach that can be used to evaluate impact effects for any combination of UAS and manned aircraft.
- WA5: **Risk Assessment**, developing a preliminary hazard analysis to characterise the interplay between threats, consequences, and barriers/mitigations for airborne conflict.

EASA have contracted QinetiQ to undertake the definition of this study to build upon the Task Force's findings and develop a technical approach that will enable the threat posed by UAS to manned aviation to be better understood.

This report details the work undertaken by QinetiQ against the requirements of Work Areas 2 to Work Areas 5. A separate report is also provided for Work Area 1 [3], which develops upon the research presented herein and presents a proposed programme of work to meet EASA's objectives.

The research described within this report includes definition of exemplar configurations that represent current popular classes of UAS. This is accompanied by description of a proven approach to generating accurate numerical (Finite Element) representations of each UAS for the purpose of collision modelling.

The challenges associated with providing an affordable and practical route for EASA to make evidence-based assessments of potential impacts between multiple permutations of UAS classes, manned aircraft types and impact locations, are discussed. An approach to achieve this is proposed, employing a combination of low- and mid-level testing and advanced numerical impact modelling.

In-line with this approach, a review of manned aircraft types and down-selection of critical impact regions is presented. In addition to down-selecting critical regions, a feature-based classification system is introduced with the objective of maximising the benefit of future research. Examples are shown as to how this would fit in with EASA's Impact Hazard Effect Assessment process.

Finally, an assessment of the causal influences and barriers associated with the risk of mid-air collisions occurring are presented along with mitigations and damage consequences, using the Bow Tie methodology. This aids future discussions of proportionate and effective preventative and mitigating measures that could be put in place to manage the risks posed by UAS operations to manned aviation.

List of Contents

1 Introduction

1.1 Background

1.1.1 In 2016, the European Aviation Safety Agency (EASA) assembled a 'Drone Collision' Task Force in response to the increasing perceived risk of collision between Unmanned Air Systems (UAS) and manned aircraft. The Task Force published its assessment of the threat [1] in October 2016, which included three key recommendations for further research and risk assessment.

1.1.1 To further this study, EASA tendered a proposal [2] with the aim to establish the baseline for subsequent coordinated and collaborative research, accounting for existing research which could be extended to satisfy the Task Force recommendations. The tender defined five Work Areas (WA) to be considered:

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- WA5: **Risk Assessment**, developing a preliminary hazard analysis to characterise the interplay between threats, consequences, and barriers/mitigations for airborne conflict.

1.1.2 EASA have contracted QinetiQ to undertake the definition of this study to build upon the Task Force's findings and develop a technical approach that will enable the threat posed by UAS to manned aviation to be better understood.

1.1.3 Whilst this study does not include any additional testing, impact modelling or quantitative vulnerability assessments, it does draw upon QinetiQ's relevant experience of testing and modelling UAS collisions. The recommendations from this study include a coherent set of work packages against which future programmes of practical work and modelling may be contracted. This construct is illustrated in Figure 1-1.

1.1.4 This document is QinetiQ's deliverable report for Work Areas 2 to 5 and is supplied to EASA in fulfilment of Deliverable D4 in QinetiQ's project plan [4].

1.1.5 A separate report is also provided for Work Area 1 [3], which develops upon the research presented herein and presents a proposed programme of work to meet EASA's requirements.

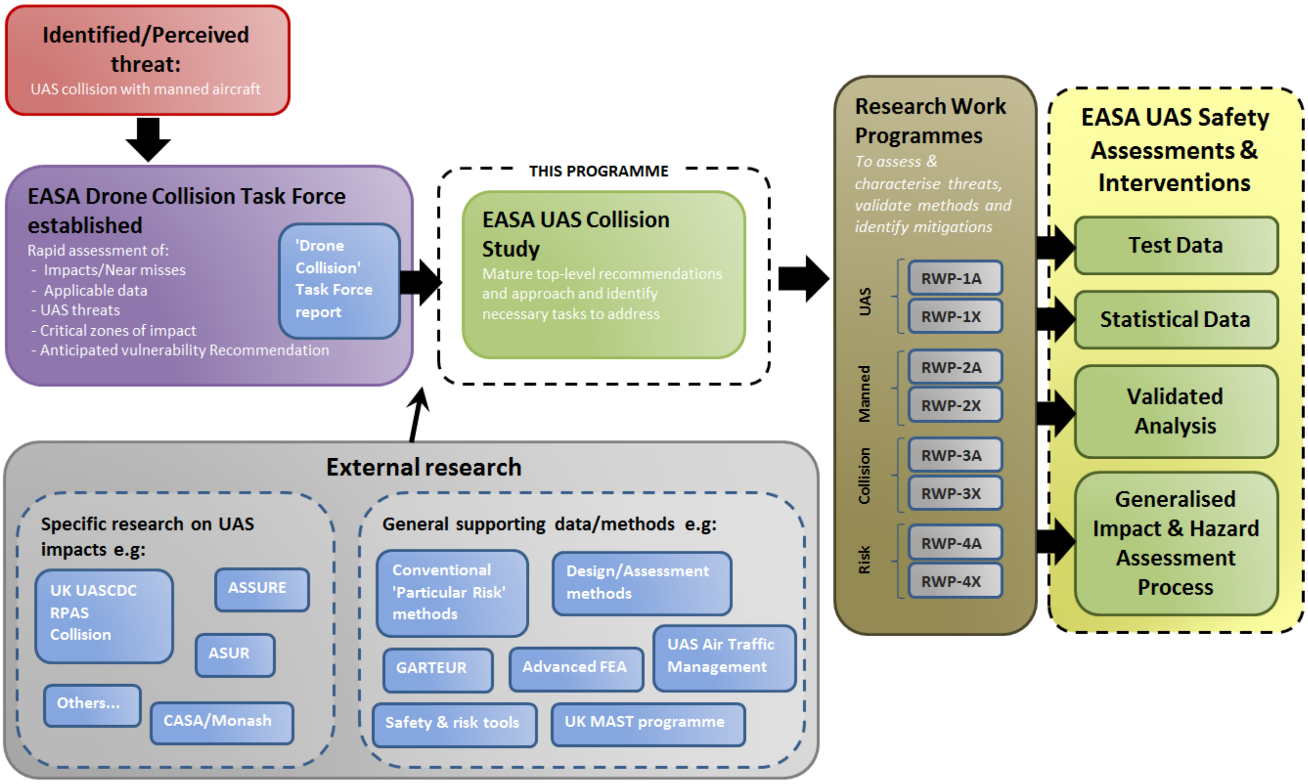

Figure 1-1: QinetiQ's interpretation of EASA's UAS collision research construct

1.2 Report structure

1.2.1 The structure of this document is aligned to the Work Areas defined by EASA.

1.2.2 Section 2 summarises the work undertaken to mature the 'UAS Threat Definition' and includes a justification of the proposed UAS mass classes, configurations and methods to develop appropriate Threat Models.

1.2.3 Section 3 outlines QinetiQ's approach to determining 'Impact Effect Assessments'. It includes a review of relevant classes of manned aircraft, prioritisation of impact locations, and a novel approach to generating test data that can be used in conjunction with modelling methods to efficiently assess a broad range of credible and high priority impact scenarios.

1.2.4 Section 4 describes QinetiQ's approach to the 'Hazard Effect Classification' activity. This discusses how the research can be aligned with the EASA impact and hazard effect assessment process and be used to make Impact Effect Assessments and determine Hazard Effect Classifications.

1.2.5 Section 5 includes a Bow Tie analysis to evaluate the threats, barriers, mitigations and consequences of a collision between a manned aircraft and UAS.

2 Work Area 2: Refinement of the UAS Threat

2.1 Introduction to Work Area 2

2.1.1 The aim of Work Area 2 is to mature the definition of the UAS threat outlined in the EASA 'Drone Collision' Task Force's Report [1] and to identify an effective and practical route to develop & validate analytical & numerical representations of the agreed configurations. This is a critical stage in the development of a UAS threat assessment methodology because it provides the data that differentiates this class of impact with other, more conventional Particular Risks such as bird strike, hail and other debris impacts.

2.1.2 Section 2.2 of the report starts by discussing the range of UAS configurations that could be encountered and proposes a small sub-set of these that should be prioritised for initial consideration. Section 2.3 explores the mass classes of these configurations before identifying specific examples of UAS/component lists to represent these down-selected mass classes, presented in Section 2.4. The method to generate numerical models of these configurations is outlined in Section 2.5 before commenting upon the potential hazards associated with high energy batteries in Section 2.6. Finally, summary recommendations for future work packages are provided in Section 2.7. The recommendations from each Work Area are translated into a proposed programme of work, which is outlined in a separate Work Area 1 report [3].

2.2 UAS types

2.2.1 In the same manner that the term 'manned aircraft' does not adequately describe the wide range of piloted air vehicles in existence, there are many examples of distinct UAS configurations.

2.2.2 The scope of this study was not explicitly constrained to a particular type of UAS, so an initial review of potential configurations was performed with the intention of identifying and justifying an appropriate down-selection. Such a down-selection is considered to be necessary in order to focus future impact effect assessments. This will enable research budgets to be directed towards impact scenarios that are perceived to have the greatest collective probability of occurrence, likelihood of causing damage and severity of outcome.

2.2.3 Figure 2-1 illustrates some of the configuration types that represent sub-classes of UAS. Note that this does not differentiate between UAS that are remotely piloted air systems (RPAS) or semi-autonomous systems, but most could be configured to operate in either mode using readily available, low cost autopilots.

2.2.4 Configurations within these sub-classes are wide-ranging and vary greatly in their size, mass, flight speed, range, altitude capability, structural robustness and ease of deployment. However, the following two sub-classes are recommended as priority cases when considering the UAS threat:

- **Quadcopters** – Priority 1 (highlighted in red in Figure 2-1). *This is the focus of the discussion and recommendations within this report.*
- **Fixed wing (electric, propeller-driven)** – Priority 2 (highlighted in orange in Figure 2-1). *Although not the primary focus of this report, it is recommended that consideration should also be given to this class of UAS.*
- **Other configurations:** Examples shown in blue in Figure 2-1 have not been selected as priorities.

2.2.5 Note that this prioritisation does not preclude future assessment of other configurations, either to reflect the findings of impact effect assessments or evolving trends in consumer and commercial usage of UAS. The recommended approach to the generation of UAS Threat Models (covered in Section 2.5) ensures that data generated can be used in a flexible manner and applied to a broad range of configurations.

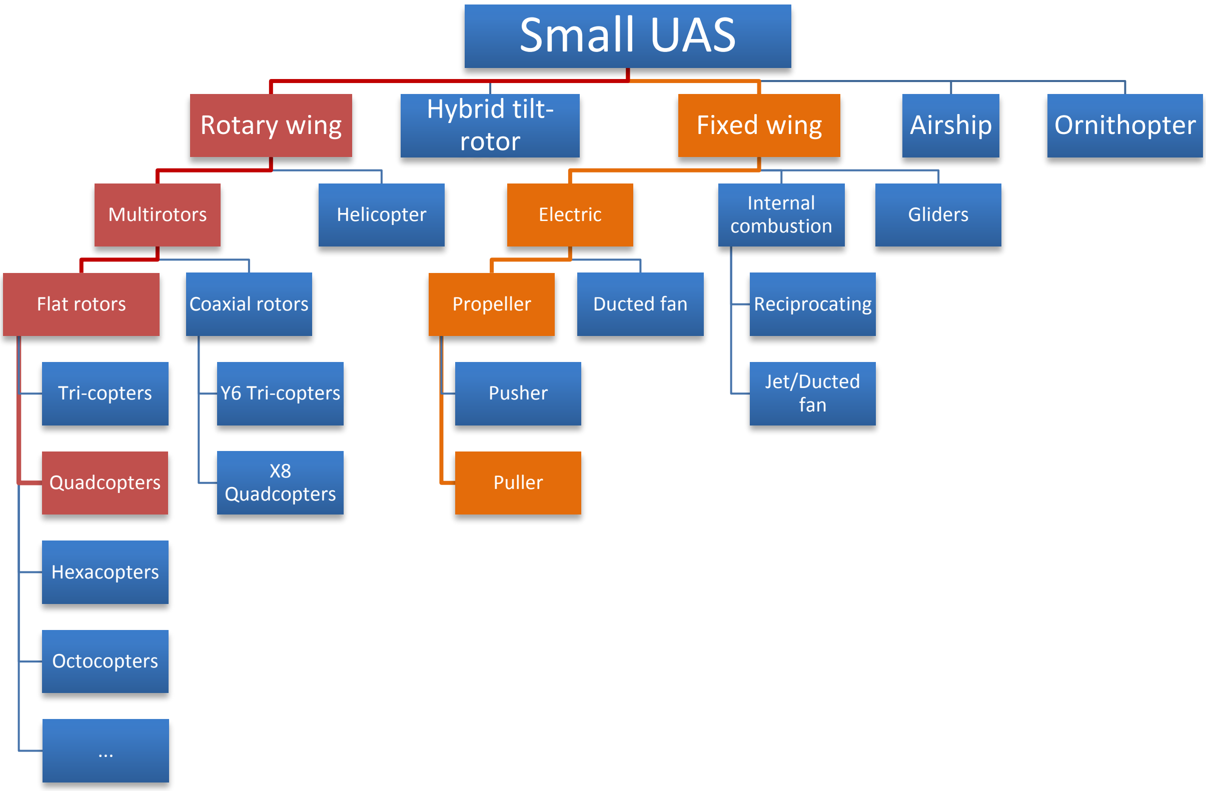

Figure 2-1: Example sub-classes of small UAS

2.2.6 Quadcopters

2.2.6.1 The rapid emergence of multirotor UAS over recent years has been greatly aided by advancements in motor, battery, flight controller, sensor and camera technologies. This class of UAS can take off from and land in confined spaces and, due to increasingly sophisticated control systems, are relatively easy to control. These characteristics, coupled with their low price-point, have led to increasingly large numbers of people adopting the technology and utilising the airspace. Furthermore, because of their ease of deployment, many users are no longer constrained to operating from traditional, organised flying clubs.

2.2.6.2 Quadcopters are currently the most popular class of multi-rotor and would therefore be an appropriate configuration to represent a large proportion of the emerging UAS market. For a given mass class, Quadcopters are also considered to represent a more severe impact threat than UAS with more rotors because:

- They require more powerful (and heavier) motors than Hexacopters/Octocopters so in the event of a collision, more energy is directed to a single impact site;
- They require smaller airframes for a given propeller diameter, thereby increasing their effective density, and;

- Impacts may occur in-line with two motors and the central fuselage, thereby resulting in multiple impacts at the same location.

2.2.6.3 It could be argued that tri-copters and coaxial configurations may present a more significant threat because they either have higher-power motors (tri-copters) or pairs of co-located motors (coaxial). However, at the time of writing, these are niche products and do not represent the majority of UAS being produced or flown.

2.2.7 Fixed wing UAS with electrically-driven propeller(s)

2.2.7.1 Fixed wing model aircraft are not a new phenomenon and have been operated by hobbyists for over half a century. Traditionally, these tended to be configured either as gliders or were powered by internal combustion engines. However, some of the same technological advances that led to the emergence of practical multi-rotor aircraft have also benefitted fixed wing configurations. Consequently electrically-powered UAS are increasingly common due to their affordability, performance, flexibility and minimal requirements for set-up/maintenance.

2.2.7.2 Larger UAS require access to appropriate airstrips and so are commonly operated within organised clubs, but low-cost electrically-driven fixed wing UAS that can be hand-launched are also widely available.

2.2.7.3 The airframes of fixed wing aircraft are typically low density, well-distributed and frangible. However, the motors (with spinners) and batteries of larger models may represent a significant threat in the event of an impact, particularly given their relatively high flight speeds compared to large multirotor UAS.

2.2.7.4 Fixed wing aircraft are also more challenging to fly than multi-rotors and have greater range and altitude capabilities. This may present a greater risk of inexperienced pilots losing sight/control of their UAS with an associated risk of unintentional and uncontrolled deviation into the path of manned aircraft.

2.2.7.5 Although fixed wing UAS may not be as prevalent as multirotor UAS, the perceived potential for long-distance run-away conditions and possible levels of damage suggest that they should also be considered within future UAS threat definition and collision assessment activities.

2.2.8 Other UAS configurations

2.2.8.1 The other UAS identified in Figure 2-1 were not prioritised for the following reasons:

- **Helicopters:** Although some helicopter systems are relatively large with powerful engines, they are not believed to be in common usage. Furthermore, because larger models are relatively complex (and expensive) machines that are harder to control, they are more likely to be piloted by trained operators. On this basis, it is considered less likely that large helicopters would be flown inappropriately at high altitudes or at extended range from the operator.
- **Hybrid tilt-rotors:** This is not currently a popular configuration in common usage.
- **Reciprocating internal combustion engine aircraft:** Whilst the engines used may pose a significant threat due to their solid construction and relatively high mass, most fixed wing aircraft now use electric propulsion systems. Internal combustion UAS are still operated from organised clubs but this is assumed to represent a minority. Research aircraft and long-endurance UAS may also utilise internal

combustion engines so although they have not been identified as a priority in this study, consideration should be given to including this class in future assessments.

- **Gas turbine aircraft:** Although these enable UAS to be flown at very high speeds, they are not in common usage.
- **Gliders:** Gliders are assumed to be highly frangible with no significant high-density or damaging systems.
- **Airships:** Airships are not in common usage and are unlikely to pose a significant impact threat, except by obscuration of vision or possibly blocking intakes.
- **Ornithopters:** Ornithopters are not in common usage.

2.3 Review of EASA proposed mass classes within the Open category

2.3.1 The EASA Task Force report [1] includes description of a proposed ‘Open Category’ which would include all UAS that are less than 25kg in mass. Within this category, the following mass classes[1] were proposed by EASA:

- ‘Harmless’[2], <0.25kg
- ‘Small’, <0.5kg
- ‘Medium’, <1.5kg
- ‘Large’, <3.5kg

2.3.2 The above mass classes are shown on a simple scale in Figure 2-2 to illustrate that they only cover a small fraction of the Open Category (the large grey region shows how little of the proposed ‘Open Category’ is catered for by mass). However, the intent of this down-selection was to capture the majority of UAS that are available on the mass market rather than to explore worst-case configurations that might be possible within the ‘Open Category’.

2.3.3 In order to test this assumption, QinetiQ has undertaken a review of current UAS products using internet-based sources and a QinetiQ database of UAS configurations. In total, over 2,000 UAS products were accounted for but this reduced to approximately 800 when filtering for commercially-available multirotors (not military or research platforms) within the 25kg Open Category. The results of this activity, carried out in Spring 2017, are illustrated in Figure 2-3, which shows the relative numbers of multirotor UAS when plotted by mass class. It can be seen from this Figure that 98% of the products included in the survey are less than 3.5kg in mass.

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1 It is assumed that these represent ‘as flown’ masses, including any installed payload. Note that this may be different from the nominal mass (without payload) or maximum take-off mass (maximum rated mass of the system if carrying a full payload).

2 ‘Harmless’ is the provisional name given to this mass class by EASA, but it should not be interpreted at this stage to mean that it has no potential to cause damage. Although the EASA naming convention has been continued within this report, it is recommended that the title given to the <0.25kg mass class be changed in order to avoid confusion when assessing damage potential.

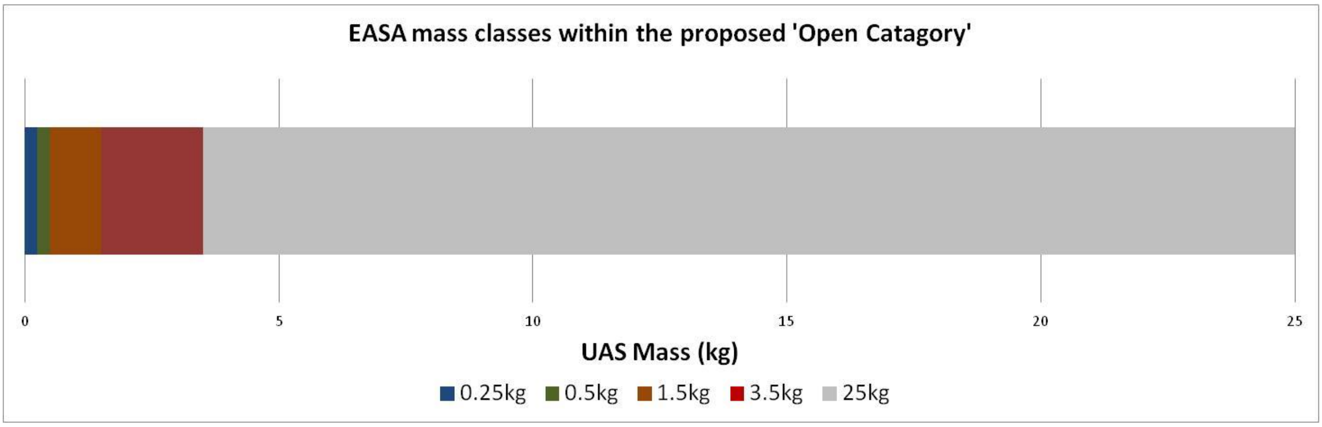


Figure 2-2: EASA proposed mass classes within the Open Category

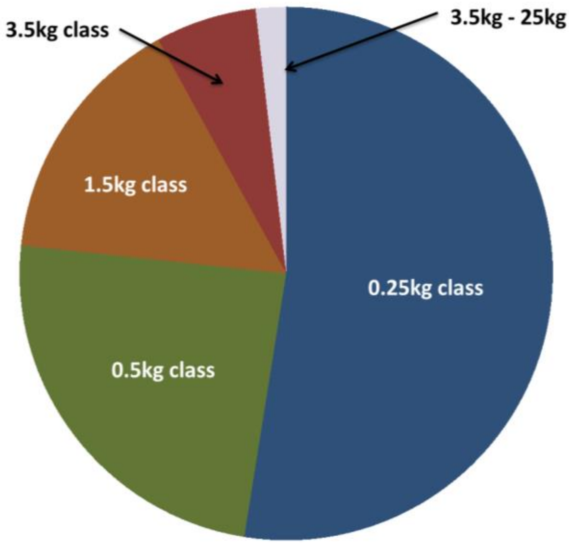


Figure 2-3: Distribution of COTS multirotor UAS product masses within the proposed 'Open Category'

2.3.4 It should be noted that because this survey did not account for the relative popularity of individual products, i.e. sales figures, the data may not reflect the true distribution of mass classes that are in current usage. However, given that the consumer/'prosumer'-grade products from the market-leading multirotor manufacturers also fall within this category, it can be concluded that the mass classes proposed by EASA meet their objective of covering the majority of multirotor UAS products currently in circulation. Furthermore, the proposed Quadcopter mass classes align reasonably well with popular products from current market-leading manufacturers, and similar derivative products from the wider market.

2.3.5 The applicability of the above data to fixed wing configurations is not assured and it is likely that the distribution of products within each mass class will be different.

2.3.6 Furthermore, the products included in this survey did not include commercial 'package delivery systems', such as those being developed by organisations such as Amazon. Although prototype systems have been demonstrated in limited trials, their designs, performance and usage are currently not considered to be sufficiently mature to allow a meaningful Threat Model to be generated. However, this is an evolving sector of the marketplace and if unmanned delivery systems do achieve commercial success, their likely combination of mass, robustness and scale in numbers would mean that it would be a high priority to understand the threat they might pose to manned aviation.

2.3.7 The mass classes of UAS that are proposed for initial Threat Modelling are summarised in Table 2-1. Whilst this concentrates upon popular classes of multi-rotors, it is recommended that once these initial studies are completed then additional configurations such as fixed wing UAS should also be evaluated.

Quadcopters		**Fixed wing (electric propulsion)**	
Mass (kg)	Mass class	Mass (kg)	Mass class
< 0.25	'Harmless'	*No fixed wing configurations identified for first phase of UAS threat assessment but future studies could be expanded to cover appropriate configurations of interest.*	
< 0.5	'Small'		
< 1.5	'Medium'		
< 3.5	'Large'		

Table 2-1: UAS mass classes

2.4 Proposed UAS threat configurations

2.4.1 The mass classes defined in Section 2.3 allow impact energies to be calculated for a given closing-velocity, but this is not sufficient to adequately characterise the threat. Although crude comparisons can be made against impact energies associated with other Particular Risks e.g. bird strike, this does not account for the significant differences in the way the energy and momentum is transferred and therefore the severity of the impact on the manned aircraft.

2.4.2 Within each mass class, a broad range of commercially available and home-built designs exist, each catering for different budgets, user requirements, and evolving styles and aesthetics. For the lighter mass classes there is a clear distinction between low-cost toy UAS and higher-performance/racing systems and this is expected to result in different impact characteristics. For example, performance-driven Quadcopters feature more-powerful motors, strong but lightweight carbon fibre composite airframes and compact high-voltage batteries (typically 3S or 4S configurations[3]); therefore a greater proportion of their total mass is accounted for in the components that are likely to be most damaging in the event of a collision. Furthermore, racing-style UAS are designed to operate at higher speeds and their smaller size means that impact forces will be concentrated on a smaller area.

2.4.3 At this stage of the UAS threat assessment process it is not considered to be practical to further sub-divide the mass classes to account for different constructions of each type of UAS[4]. However, it is necessary to agree the configuration of each of the down-selected UAS classes, as defined in Table 2-1.

[3] '3S' and '4S' refers to the number of individual cells that are arranged in series within the battery, and therefore its nominal voltage.

[4] Once the basic threat has been evaluated, the methods and data generated will allow specific configurations to be assessed and/or best practice designs to be developed.

2.4.4 The following sections outline proposed configurations to represent each of the UAS threat classes. Each configuration is illustrated by a commercially available example product as well as a more generic list of primary components[5].

2.4.5 In order to provide an additional level of validation of the generic configurations, they have been assessed using a commercially-available UAS performance estimation toolset, ‘eCalc’ [5]. The primary use of this tool was to make sure that the selected components were broadly compatible and provide indication of likely maximum flight speeds, though this was subject to some interpretation. This performance assessment was considered to be particularly relevant to the ‘Harmless’ and ‘Small’ configurations, which are based upon generic examples of small, inexpensive consumer-level racing systems, where manufacturers do not typically provide detailed/reliable performance specifications.

2.4.6 ‘Harmless’ <0.25kg Quadcopters

2.4.6.1 The proposed configuration is based upon an inexpensive, entry-level small First-Person View (FPV) racer configuration with a compact, 120mm carbon fibre composite frame (dimension measured between diagonally-opposed motor centres).

Figure 2-4: Example 0.25kg (‘Harmless’) class Quadcopter

2.4.6.2 Figure 2-4 shows an example commercial product to illustrate this configuration and Table 2-2 provides a breakdown of components. Note that because this is a performance-

[5] The primary components are those which are expected to be most damaging in the event of a collision and typically include the motors, battery, frame and in some cases, cameras.

focused configuration, the motors are slightly heavier than those assumed in the EASA Task Force Report [1].

2.4.6.3 In the event of a collision, this selected configuration is judged to represent a more severe threat than lower performance toy systems within the same mass class. It is therefore considered to represent a configuration that is closer to the upper-bound, rather than typical, threat.

UAS type	Quadcopter		
Mass class	0.25kg		
Mass class descriptor	'Harmless'		
Example COTS product	Eachine Falcon 120		
	http://www.eachine.com/index.php?com=search&keywords=falcon%20120		
Primary components	**Description**	**No. Off**	**Mass (each)**
Frame	120mm carbon frame	1	32g
Battery	3S LiPo, 850mAh (possibly Turnigy 4S 850)	1	69g
Motors	1306 3500KV	4	11.5g
Secondary components	**Description**	**No. Off**	**Mass (each)**
Camera	700TVL CMOS FPV camera	1	12g
Flight controller	Inc. ESC	1	6g
Receiver	Lightweight (no case)	1	2g
FPV transmitter		1	6g
FPV antenna		1	17g
Wiring & lighting		1	
Propellers	3030-4	4	10g

Table 2-2: 'Harmless' <0.25kg Quadcopter definition

2.4.6.4 This configuration has been evaluated using the 'xcopterCalc' module within eCalc to provide an estimate of its performance and validate the selection of primary components. Although some components were not available in the eCalc database e.g. specific model of motor, these were substituted for similar alternatives or defined as custom entries.

2.4.6.5 The eCalc analysis provides confidence that the generalised configuration is viable (though a lower-pitch propeller is recommended), and estimates the maximum air speed of the system to be approximately 28ms^{-1} when using a 3S battery[6]. No reliable maximum speed data is available from the manufacturer of the example commercially available system.

2.4.7 'Small' <0.5kg Quadcopters

2.4.7.1 The proposed configuration is based upon an inexpensive, entry-level FPV racer configuration with a 220mm carbon fibre composite frame.

2.4.7.2 Figure 2-5 shows an example commercial product to illustrate this configuration and Table 2-3 provides a breakdown of components. Note that because this is a performance-focused configuration, the motors are slightly heavier than those assumed in the EASA Task Force Report [1].

2.4.7.3 Similar to the 0.25kg class Quadcopter, the selected configuration is judged to represent a more severe threat than lower performance toy systems within the same mass class.

[6] Maximum air speed is at maximum power and level flight, but neglects aerodynamic drag. Actual maximum air speed will therefore be less than this.

Figure 2-5: Example 0.5kg ('Small') class Quadcopter

UAS type	Quadcopter		
Mass class	0.5kg		
Mass class descriptor	'Small'		
Example COTS product	Eachine Wizard 220		
	http://www.eachine.com/index.php?com=search&keywords=wizard		
Primary components	**Description**	**No. Off**	**Mass (each)**
Frame	220mm carbon frame	1	160g
Battery	3S LiPo, 1500mAh	1	130g
Motors	2205 2300KV	4	25g
Secondary components	**Description**	**No. Off**	**Mass (each)**
Camera	700TVL CMOS FPV camera	1	12g
Flight controller		1	6g
Receiver	Lightweight (no case)	1	15g
ESC	20A ESC	4	8g
FPV transmitter		1	7g
FPV antenna		1	
Wiring & lighting		1	
Propellers	5040-3	4	7g

Table 2-3: 'Small' <0.5kg Quadcopter definition

2.4.7.4 As before, this configuration has been modelled using the 'xcopterCalc' module within eCalc, with custom entries where exact components were not available.

2.4.7.5 The eCalc analysis provides confidence that the generalised configuration is viable (though a lower-pitch propeller is recommended), and estimates the maximum air speed of the system to be approximately $25ms^{-1}$ when using a 3S battery. Note that this is relatively slow for genuine racing UAS, but it is more representative of consumer-level configurations. No reliable maximum speed data is available from the manufacturer of the example commercially available system.

2.4.8 'Medium' <1.5kg Quadcopters

2.4.8.1 The proposed configuration for the 'Medium' Quadcopter class is based upon the popular DJI Phantom family of products. The configuration of this example is outlined in Table 2-4.

UAS type	Quadcopter		
Mass class	1.5kg		
Mass class descriptor	'Medium'		
Example COTS product	DJI Phantom 4		
	http://www.dji.com/phantom-4/info#specs		
Primary components	**Description**	**No. Off**	**Mass (each)**
Frame	350mm Plastic frame	1	177g
Battery	4S LiPo, 5350mAh	1	462g
Motors	2312 960KV	4	53g
Secondary components	**Description**	**No. Off**	**Mass (each)**
Camera	Small gimbaled camera	1	
Flight controller		1	
Receiver		1	
ESC		4	
Transmitter		1	
GPS module		1	
Wiring, lighting & sensors		1	
Propellers	9450-2	4	

Table 2-4: 'Medium' <1.5kg Quadcopter definition

2.4.8.2 The maximum air speed of this configuration is $20ms^{-1}$. It is also capable of flying at altitudes of up to 6,000m above sea level; however, it is limited by software to a maximum altitude of 500m above its take-off position[7].

2.4.9 'Large' <3.5kg Quadcopters

2.4.9.1 The proposed configuration for the 'Large' Quadcopter class is based upon the popular high-end DJI Inspire family of products. The configuration of this example is outlined in Table 2-5.

[7] Altitude limitations are noted here because they would affect both the probability of collisions occurring and also the likely impact velocity. Whilst it might be assumed that the velocity of the UAS is independent of altitude, larger manned aircraft e.g. airliners, operate at greatly reduced velocities at lower altitudes.

UAS type	Quadcopter		
Mass class	3.5kg		
Mass class descriptor	'Large'		
Example COTS product	DJI Inspire 1 (with camera payload)		
	http://www.dji.com/inspire-1/info#specs		
Primary components	**Description**	**No. Off**	**Mass (each)**
Frame	580mm carbon, plastic & magnesium alloy	1	TBC
Battery	6S LiPo, 5700mAh	1	670g
Motors	3510 350KV	4	106g
Camera & gimbal		1	530g
Secondary components	**Description**	**No. Off**	**Mass (each)**
Flight controller		1	
Receiver		1	
ESC		4	
Transmitter		1	
GPS module		1	
Wiring, lighting & sensors		1	
Propellers	1345-2	4	

Table 2-5: 'Large' <3.5kg Quadcopter definition

2.4.9.2 The maximum air speed of this configuration is $22ms^{-1}$. It is also capable of flying at altitudes of up to 4,500m above sea level; however, it is limited by software to a maximum altitude of 500m above its take-off position.

2.5 UAS Threat Models

2.5.1 In order to accurately predict the effect that a UAS will have upon a manned aircraft in the event of a collision, it is necessary to characterise the response of the UAS at both component level and at system level. This requires the development of accurate representations of the components and appropriate definition of how they interact as part of an assembly.

2.5.2 The primary components used to define each of the UAS threat configurations in Section 2.4, and which make-up the majority of the total UAS mass, are as follows:

- Battery;
- Motor(s);
- Frame (if judged to be significant to the response);
- Camera (if applicable);
- Spinner (for fixed wing propeller driven UAS).

2.5.3 In previous QinetiQ studies, other components such as flight controllers, receivers, transmitters, electronic speed controllers, antennae, wiring, and propellers were considered to be of lower importance in the event of a collision. This is because they are lightweight, frangible, low-stiffness and/or distributed throughout the airframe.

2.5.4 Thus, provided that the rationale for excluding the secondary components remains valid for each configuration of interest, the UAS Threat Models would only need to consider an assembly of the primary components. These simplifications have the additional benefit of reducing the complexity of both the test articles and their corresponding numerical models, which thereby reduces uncertainty when comparing the numerical models and experimental results.

2.5.5 The proposed route to developing accurate and adaptable UAS Threat Models is based upon successful methodologies developed on other related programmes. The development of these Threat Models was based on Finite Element modelling with validation via test. An example of a validated FE-based UAS Threat Model, along with photographs of the components, (representative of the 'Medium' class) is shown in Figure 2-6.

2.5.6 A critical stage in the development and validation of Finite Element UAS Threat Models is the representation of the primary components as simplified 'equivalent materials' that respond correctly during impact. This is described further in Section 2.5.8. A benefit of characterising and validating the response of the UAS at the component level is that Threat Models can be rapidly updated to reflect technological advances and evolving trends as new UAS products become available. In some cases this may not require any further characterisation work i.e. where new products utilise similar component-sets, but if new data is required then it can be developed within short timeframes.

2.5.7 In the example shown in Figure 2-6 it was necessary to include a representation of the frame structure as well as the battery and motors; this is because it was shown, during testing, to have a significant effect on the impact response.

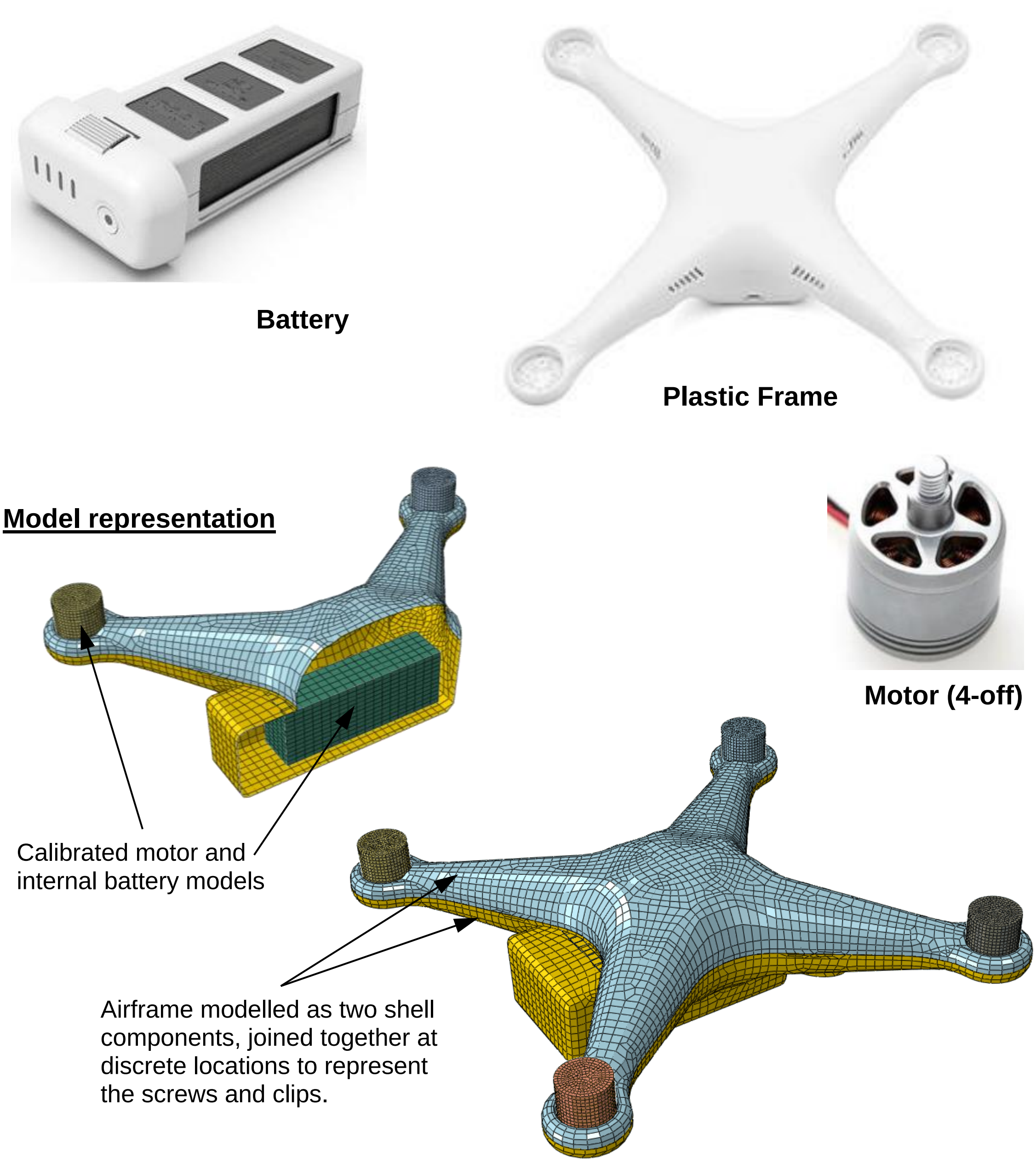


Figure 2-6: Photographs and QinetiQ model representation of a 'Medium' UAS

2.5.8 UAS component testing

2.5.8.1 Components such as the motors, batteries and cameras are complex assembly structures composed of a variety of different materials. To represent the detailed construction of these items in a simulation would be onerous, inefficient and unnecessary for the vast majority of impact cases.

2.5.8.2 The proposed approach is therefore to consider each of these parts as a homogeneous material, characterised by a combination of static crush and dynamic impact tests. These components can then be considered as primitive geometries but with calibrated material models e.g. non-linear stress-strain response curves, such that, when they are used to simulate impacts against target structures, the forces that they impart are realistic.

2.5.8.3 Static crush tests on components, such as those shown in Figure 2-7, will classify component compressive behaviour in terms of force-displacement. This enables a partial material model (uniaxial stress-strain response) to be generated for each component.

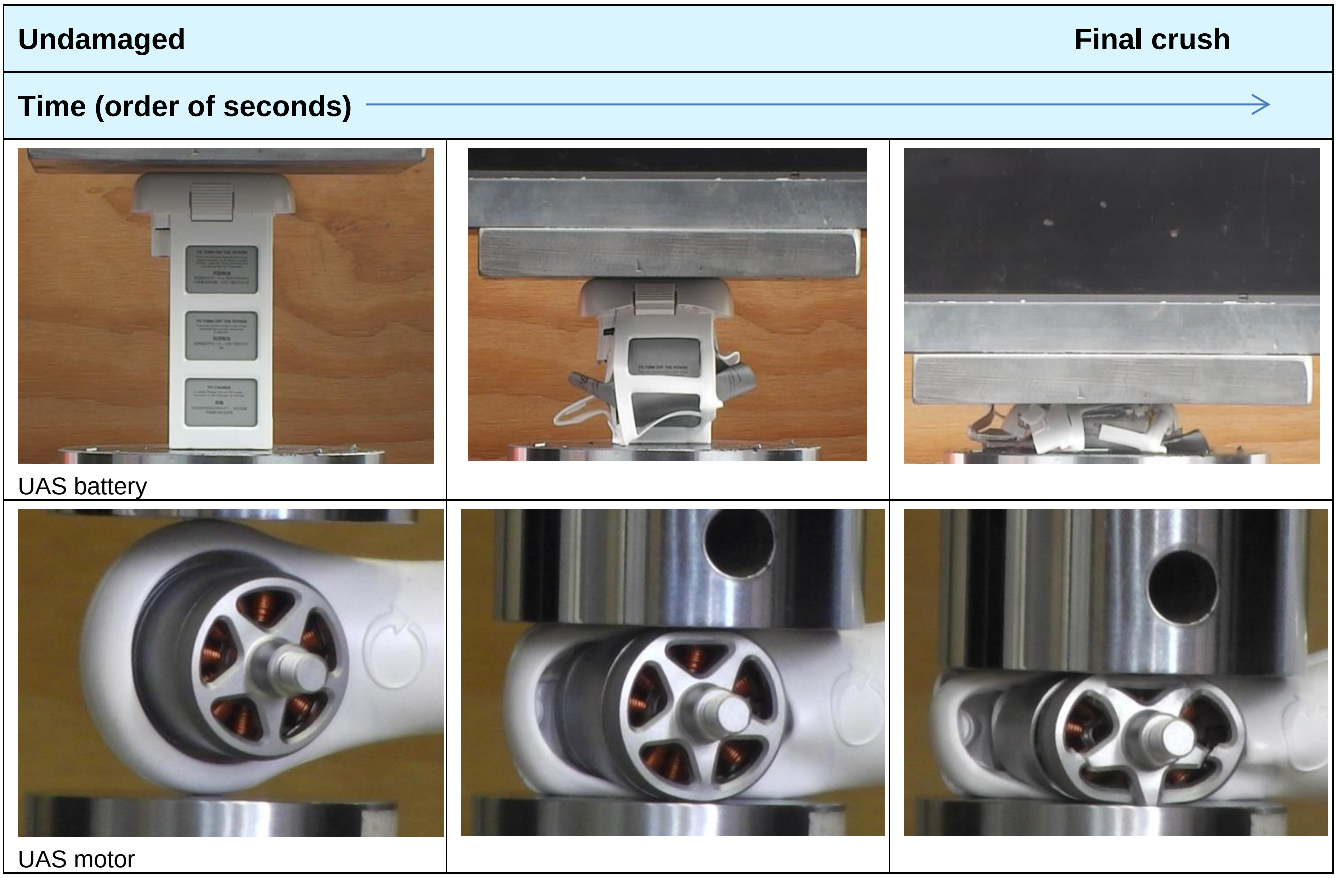


Figure 2-7: Images of components during QinetiQ static crush testing

2.5.8.4 By further implementing high-speed impact testing against an instrumented target, such as the Hopkinson bar shown in Figure 2-8, information on the dynamic response of each component can be obtained to complete the material model.

2.5.8.5 Figure 2-9 shows an example normalised force history for a dynamic test of an UAS motor along with the equivalent impact response predicted by Finite Element analysis; it highlights the difference between the material model created from crush data and the final calibrated material model.

2.5.8.6 Once calibrated, these equivalent materials and associated geometric representations of the components can then be utilised alongside representations of any additional components e.g. frames, to form a Finite Element representation of each UAS i.e. a ‘Threat Model’.

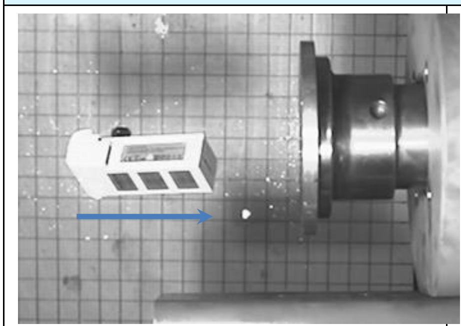
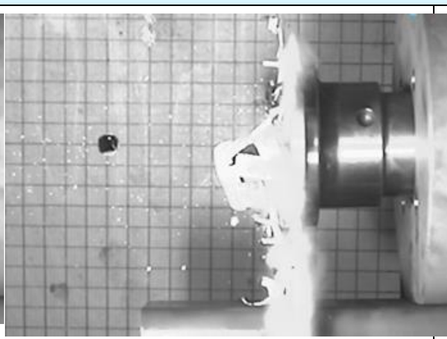
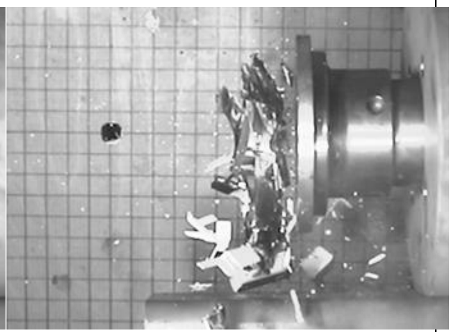
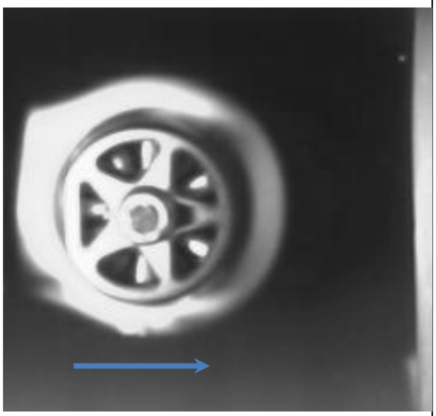
Undamaged at initial velocity		**Post-impact**
Time (order of milliseconds) →		
 UAS battery		
 UAS motor		

Figure 2-8: Images of components during QinetiQ dynamic impact testing

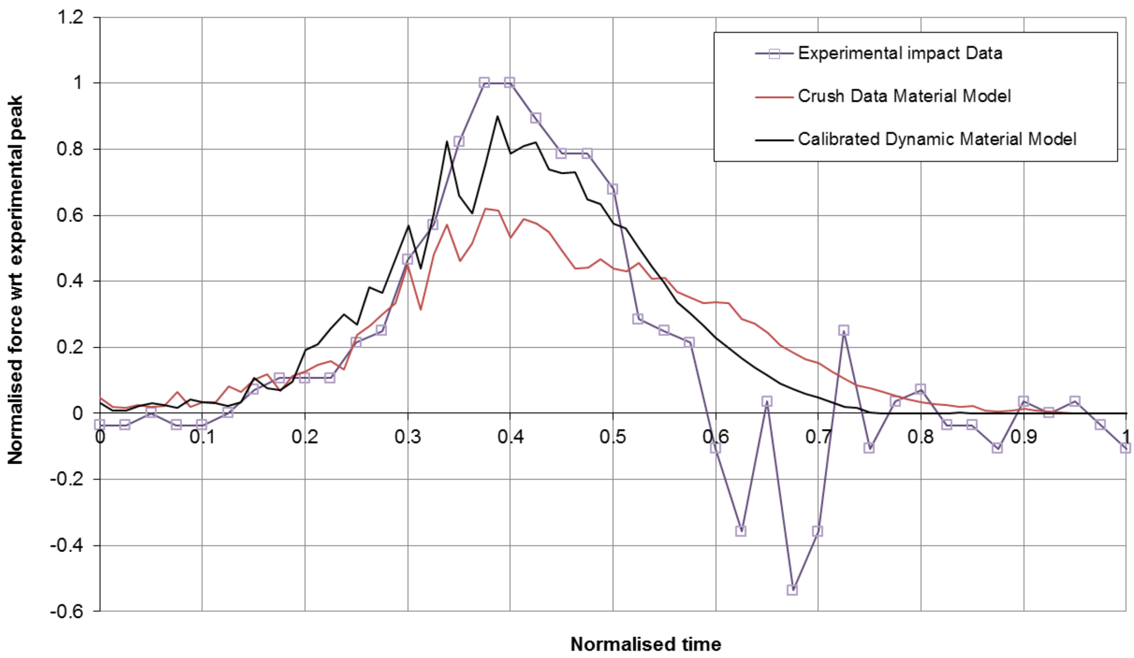


Figure 2-9: Calibration results (normalised) of dynamically tested motor

2.6 Threats posed by lithium-polymer (LiPo) and lithium iron phosphate (LiFePO) batteries

2.6.1 In addition to the mechanical threat posed by UAS, concerns were raised in the Task Force report [1] that the high energy density LiPo or LiFePO batteries used in UAS could ignite or explode if damaged during an impact.

2.6.2 It is well documented[8] that these batteries can ignite if they are 'shorted out' (closed circuit). Although some batteries have protection circuits to mitigate risks of inadvertently connecting the terminals, this would not offer any protection when the short occurs internally due to deformation, damage or intrusion of a foreign body.

2.6.3 Although this threat can not be ruled out, QinetiQ has performed approximately 30 impact and crush tests using charged LiPo and LiFePO batteries, none were observed to exhibit explosive behaviour.

2.6.4 The level of damage sustained varied greatly across all of these tests, with some remaining functional (despite damaged casings), others being badly damaged and non-functional, and some being completely destroyed.

2.6.5 The most severe reaction that was observed during these tests was some smouldering (smoke and possibly small flames) during a slow crush test. However, it should be noted that the batteries were reduced to a relatively low level of charge for the crush tests, but they were fully charged for the impacts. In all cases, the potential risks were identified and managed during testing.

[8] A search on 'Youtube' will reveal numerous examples of batteries spontaneously, and sometimes violently, igniting when nails are driven through them to short the cells.

2.6.6 Additional testing for the development of Threat Models will further expand this dataset and if necessary, greater attention could be given to acquiring data on the battery response.

2.7 Recommended actions from Work Area 2

2.7.1 The following recommendations are made in support of the development of UAS Threat Models:

1. Validated FE-based Threat Models should be developed for each of the four proposed classes of Quadcopter. This should include the following activities:
    a. Crush testing and impact testing of primary UAS components.
    b. Develop and calibrate FE representations of primary components.
    c. Construct FE models of each UAS threat, suitable for use in dynamic explicit impact analyses.
    d. Demonstrate each UAS Threat Model in FE-based impact analysis against a rigid target.

2. Impact testing of conventional Particular Risk projectiles (e.g. hail, birds, engine fragments and possibly tyre debris) should also be conducted against instrumented targets. This will enable direct comparison of the transient impact forces associated with UAS impacts and threats that have already been met during certification. Although some similar data may exist, it is either not readily available/publishable and/or insufficient details are known about its acquisition to enable a direct comparison with UAS data.

3. As a lower priority (follow-on activity), expand UAS Threat Models to include additional UAS types such as electrically-powered fixed wing systems. This would follow the same developmental process as above.

3 Work Area 3: Impact Effect Assessment

3.1 Introduction to Work Area 3

3.1.1 This Work Area considers the locations at which impacts might occur for the various different classes of manned aircraft. Work Area 3 also identifies a route to efficiently generate data that will enable the effect of UAS impacts against a broad range of manned aircraft to be assessed.

3.1.2 Section 3.2 contains a summary of aircraft types (by Certification Specification) that may be at risk of colliding with a UAS. Section 3.3 then goes on to identify the zones of these aircraft that are considered to be at greatest risk of being impacted in the event of such a collision. Also included in Section 3.3 is a description of the approach that is being used both to aid the further prioritisation of critical impact locations across the different aircraft classes, and also to explore similarities between classes. The purpose of exposing structural similarities is to actively seek opportunities that enable impact effect assessment (IEA) results to be either 'read-across' between classes or demonstrated by suitably validated simulation, thereby maximising the benefits of any physical test results or detailed analysis.

3.1.3 Section 3.4 provides a summary of the features that have been down-selected from the aircraft impact zone analysis, followed by a description of the proposed feature-based assessment in Section 3.5. Finally, recommendations from this Work Area are included in Section 3.8.

3.2 Review of manned aircraft classes

3.2.1 The threat of UAS impact is not unique to any specific class of manned aircraft, though the probability of occurrence and severity of the outcome may vary significantly between classes and individual models.

3.2.2 An initial activity within this Work Area was to identify the types of manned aircraft (by Certification Specification) that could be subject to UAS collisions. The output from this activity is summarised in Table 3-1, which also includes examples of each of the main aircraft types.

Certification	Type	Exemplar	Notes
CS-22	**Gliders**	Schleicher ASK 23	General club glider - Many alternatives Could split into club vs competition sub-classes
CS-23	**CS-23 Jet**	Cessna Citation 510	Popular business jet
	CS-23 Single Propeller	Cessna 172	Most produced aircraft
	CS-23 Aerobatic	Extra 300	Representative aerobatic aircraft
CS-25	**Civil Airliner (metallic)**	A320	Very popular airliner, particularly within Europe
	Civil Airliner (composite)	B787	High proportion of composites used
CS-27	**Small Rotorcraft**	Robinson R44	Best selling general aviation helicopter since 1999
CS-29	**Large helicopters**	AS332 Super Puma	Civil operated Large Rotorcraft
CS-31	**Balloons**	*These classes not explicitly considered within this initial down-selection activity. However, this does not mean that collision assessments could not be made for these classes using data generated for larger aircraft.*	
CS-LSA	**Light Sport Aeroplanes**		
CS-VLA	**Very Light Aeroplanes**		
CS-VLR	**Very Light Rotorcraft**		

Table 3-1: Manned aircraft examples by Certification Specification

3.2.3 Note that in some cases a broad range of aircraft are encompassed by a single Certification Specification and in these instances, the category has been sub-divided further. For example the CS-23 class has been split into three different categories to cover small single propeller aircraft, small jets, and aerobatic aircraft.

3.2.4 Similarly, the CS-25 'Large Aeroplanes' class has been split into two categories to distinguish between traditional metallic airframes and more modern airframes with greater application of composite materials[9]. This distinction was considered to be necessary because composite components may respond differently to UAS impacts than metallic configurations, even if certified to the same standards. It is also worthy of note that damage mechanisms and thresholds are significantly different for composite materials and although collision events that result in penetration/severe damage may be of greatest concern, less severe impacts may be sufficient to result in Barely Visible Impact Damage (BVID) that could undermine the structural integrity whilst not being immediately detected.

3.3 Review of aircraft impact zones

3.3.1 The aircraft impact zones identified in Section 6.2.1 of the EASA 'Drone Collision' Task Force report [1] were reviewed and are considered to be appropriate. However, it is noted that the list of potentially critical impact zones is extensive and would require considerable effort to assess experimentally, even for a single combination of manned aircraft and UAS. This would be further compounded by consideration of multiple aircraft types, UAS types and impact velocities. On this basis, it is assumed that comprehensive testing (using a similar approach as for demonstrating compliance of individual aircraft models against established Particular Risk requirements) would not be a practical or economically attractive means by which to achieve EASA's objectives.

3.3.2 It is understood that EASA's current requirement is to develop understanding of the threat posed by UAS so that informed and proportionate decisions can be made to manage the risks to manned aviation. Ideally the consequences of collisions involving all classes of manned aircraft and UAS would be well understood, but it is recognised that research activities will need to be prioritised to make best use of available resources.

3.3.3 When generating certification evidence against impact requirements, it is not uncommon for Design Organisations to justify compliance statements for multiple zones by 'read-across' of test results for similar (but not identical) locations or features. Alternatively, modelling methods are validated against individual test conditions and are then used to explore derivative designs. Similar approaches might be expected when assessing the UAS threat, whereupon it might be assumed – as a first approximation – that all aircraft within the same class/sub-class (as defined in Table 3-1) would exhibit similar damage thresholds.

3.3.4 If future research activities were to be focussed upon a specific class/sub-class of manned aircraft and single UAS threat then the most accurate method of determining the effect of collisions would be to undertake UAS impact tests against down-selected regions of genuine airframe structures. However, as noted above, whilst this approach may be appropriate for certification purposes, it would not be an efficient means by which to generate more-general vulnerability data that could be applied to multiple classes of

[9] Note that some aircraft, which might not be considered to be 'composite airframes', include composite components that could be subject to impacts. Whilst these do not fall neatly into the categorisation proposed here, the inclusion of both metallic and composite airframes is sufficient to ensure that both material families are considered.

aircraft. Furthermore, since there is a strong likelihood that UAS designs will continue to evolve rapidly, the long-term validity of the results could not be assured and a more flexible approach would be beneficial.

3.3.5 It is therefore postured that the wide variety of impact locations across multiple aircraft types could be characterised by their general structural configuration and their material class. For example, discretely-stiffened/monolithic aluminium alloy panels are a common feature across many classes of manned aircraft, so simplified tests to determine their resistance to UAS impacts would provide 'read across' opportunities and a basis by which to apply engineering judgement. Such tests would also provide a means by which to validate Finite Element based models which could be used to extend the dataset available for read-across (by analysis of many permutations of simple panel features) and also provide more detailed analyses of specific configurations (using high-fidelity modelling of aircraft sub-assemblies).

3.3.6 An activity has therefore been undertaken to review the impact zones on each class of manned aircraft and identify - using open-source data - the underlying structural detail and material usage.

3.3.7 The impact zones identified in the Task Force report [1] have been reproduced in a spreadsheet[10], with separate worksheets for each of the exemplar aircraft identified in Table 3-1. This spreadsheet has been used to undertake a preliminary, judgement-based, review of the critical areas on each of the different classes (and sub-classes) of aircraft. It must be stressed that the purpose of this initial review was to aid the prioritisation of critical impact regions/features rather than to determine, without additional evidence, the effect of specific collision events.

3.3.8 The following have been qualitatively assessed for each of the impact zones on each of the example aircraft types:

1. Likely impact angle and threat classification.
2. Prioritisation of critical areas.
3. Categorisation of aircraft impact zones into feature types.

3.3.9 Impact angle and threat classification

3.3.9.1 For each impact location, the likely angles of impact have been assessed using the criteria described in Table 3-2. This table also describes how the mode of damage is classified. In most cases, the mode of damage was identified to be 'Deformation/Penetration' of the structure or for engines, 'Ingestion'.

10 The spreadsheet was a 'working document' and has not been included within this report. However, the process and results are discussed.

Impact angle and threat classification			
Title	**Ranking**	**Description**	
Impact	Anticipated angle/direction of impact.	**Direct frontal**	Impacts to the component are within 30 degrees of the surface normal
		Intermediate	Impacts between 30 and 60 degrees to the surface normal
		Glancing	Impacts likely to be at angles of greater than 60 degrees to the surface normal
		Edge impact	Impacts against panel edges e.g. Gear bay doors (Note that impacts against rotor blades or similar are counted as Direct Frontal rather than Edge)
		Sideways/Rearwards	Impacts to the side or rear of the aircraft (only applicable for rotorcraft)
Threat type	Primary mode of damage that might be expected from an impact.	**Deformation/Penetration**	Structural damage
		Ingestion	Ingestion into engines
		Obstruction	Obstruction of inlets/vents e.g. Engine air intakes
		Mechanism jamming	Fouling with mechanisms e.g. Debris in flap deployment mechanism
		Damage to systems	Damage to pipework, sensors, cabling etc.

Table 3-2: Impact threat classification - Taxonomy

3.3.10 Prioritisation of critical areas

3.3.10.1 For each class of manned aircraft, an initial down-selection was undertaken to identify the regions/components that should be prioritised for a more detailed impact assessment.

3.3.10.2 The criteria used to determine initial priorities is outlined in Table 3-3 and includes reference to the likelihood that each area would be impacted (based upon its relative size and location), the criticality of the region/component to the safe operation of the aircraft, and the anticipated vulnerability of the region to damage.

3.3.10.3 When estimating the vulnerability of each impact area, it was assumed that the collision was against a 'Large' UAS (defined in Section 2.3) at velocities appropriate for the class of vehicle when operating at altitudes of less than 10,000ft. Where significant doubt existed about the level of damage that might be inflicted, a more conservative grading was applied i.e. a greater level of damage was assumed.

3.3.10.4 It should be noted that this prioritisation process was subject to many assumptions and must not be interpreted as a robust safety assessment. Instead, it represents a preliminary 'best guess' to inform the prioritisation of more-detailed assessments. As results are generated from further work, the priorities should be revisited in order to ensure that research activities provide best value.

Prioritisation of critical areas			
Title		**Taxonomy description**	
Perceived probability of impact	Relative likelihood of a region/component being involved in an impact. This will be based upon the feature size and location on the aircraft.	**Low**	Small features or areas that are unlikely to be exposed to impacts e.g. Lights or small sensors.
		Medium	Regions with moderate area that are exposed to potential impacts e.g. Nacelles or winglets.
		High	Regions with large areas that would be prone to impacts e.g. Windshields or wing leading edges.
Preliminary Hazard Effect Classification (Component criticality)	Criticality of a region/component to the safe and effective operation of the aircraft. Note: <u>Approximate</u> correlation to EASA Task Force taxonomy.	**Low (HEC-4/5)**	Damage/Failure would not significantly compromise the safe operation of the aircraft.
		Medium (HEC-3)	Damage/Failure would reduce the capability of the aircraft and/or present an increased threat to the safety of the aircraft and crew.
		High (HEC-2)	Damage/Failure would present a serious threat to the safety of the aircraft and crew.
		Extreme (HEC-1)	Damage/Failure would present an immediate and grave threat to the safety of the aircraft and crew.
Preliminary Impact Effect Assessment (Vulnerability)	Anticipated likelihood of damaging a region/component if impacted.	**Low**	Unlikely to be damaged by an impact - Possibly minor dents/scratches
		Medium	Damage is likely - Deformation of the structure
		High	High risk of penetration/major deformation/part detachment
Proposed priority	Priority ranking based upon the assessment of probability, criticality and vulnerability.	**Low**	Low priority - Qualitative assessment suggests that risk to safety is relatively low
		Medium	Medium priority - Should be investigated once the high priority cases have been evaluated
		High	High priority - Should be investigated as soon as possible

Table 3-3: Prioritisation of critical areas - Taxonomy

3.3.11 Categorisation of aircraft impact zones

3.3.11.1 Each of the aircraft impact zones have been categorised in accordance with Table 3-4. This identifies the structural configuration and materials that would be typically be used for each of the aircraft.

3.3.11.2 It should be noted that the configuration information used for this assessment is based upon best available data and may not be accurate for all features and all aircraft within each class. However, the purpose of this exercise is to identify trends rather than to provide detailed design information associated with specific aircraft; therefore minor discrepancies are unlikely to be significant.

3.3.11.3 Furthermore, it is recognised that some materials e.g. GLARE, are not included in this survey. Whilst it was not the intention to exclude any particular materials, it was necessary to consider only widely used families of material for the purpose of these early studies into UAS collision threats.

Categorisation of impact zones			
Title		**Taxonomy description**	
Feature types	Structure of the region/ component.	**Monolithic/Stiffened panel (flat-ish)**	Monolithic or discretely stiffened panels that are flat or lightly-curved.
		Monolithic/Stiffened panel (curved)	Monolithic or discretely stiffened panels with moderate curvature e.g. Nose cones or wing root fairings
		Monolithic/Stiffened panel (tightly curved)	Monolithic or discretely stiffened panels with moderate curvature e.g. Engine nacelle LEs or empennage LE.
		Sandwich panel (flat-ish)	Sandwich panels that are flat or lightly-curved.
		Sandwich panel (curved)	Sandwich panels with moderate curvature e.g. Nose radome (if applicable)
		Sandwich panel/Core (tightly curved)	Sandwich panels with moderate curvature e.g. Engine nacelle LEs or empennage LE
		Solid section	E.g. Landing gear components
		Transparency	E.g. Windscreens, light covers
		Jet engine	Ingestion is defined as a separate category.
		Propellers/Rotors	
		Other	
Materials	Material class of the region/ component.	**Metallic**	E.g. Aluminium alloys, steels etc.
		Carbon composites	Carbon fibre-based composites
		Glass composites	Glass fibre-based composites
		Quartz/Aramid composites	Quartz/Aramid fibre-based hybrid composites (typically for radomes)
		Monolithic glass/Acrylic	Glass or Acrylic bulk materials (for transparencies)
		Laminated glass/Acrylic	Glass and/or Acrylic laminates, including any additional interlayers (for transparencies)

Table 3-4: Categorisation of impact zones

3.3.12 Survey process

3.3.12.1 The spreadsheet-based evaluation has been completed by QinetiQ, largely based upon engineering judgement and available data. A copy of the draft evaluation was sent to EASA for review and has been the subject of discussions in meetings and videoconferences.

3.3.12.2 An analysis of the results of this exercise is described in Section 3.4 which illustrates how the data is intended to be used.

3.4 Survey results

3.4.1 Results from the review of impact zones (Section 3.3) have been analysed. The objectives of this analysis were to identify:

- The aircraft impact zones that should be prioritised;

- Similarities between critical impact zones, and the associated potential to minimise the number of test activities, and;
- Applicability of proposed test data to impact regions on all manned aircraft types, including lower priority cases *i.e. 'Even if testing was aimed at providing data for high priority impact scenarios, can it also be used to provide assessments for medium and low priority cases, or for small, General Aviation classes of aircraft?'*

3.4.2 Prioritising and grouping by feature type

3.4.2.1 The processed results of the survey are illustrated in Figure 3-1. This shows how the data has been filtered to identify the structural features that should be prioritised and also how these fall into common 'families' of feature types. The number in each of the boxes represents the number of impact regions represented at each stage of the process. This filtering process was achieved through the following steps:

1. The 'High' priority regions for each aircraft type were selected, discounting the 'Medium' and 'Low' priority regions.
2. Where appropriate the feature types are split by basic construction and material.
3. Example components were identified corresponding to the down-selected features.

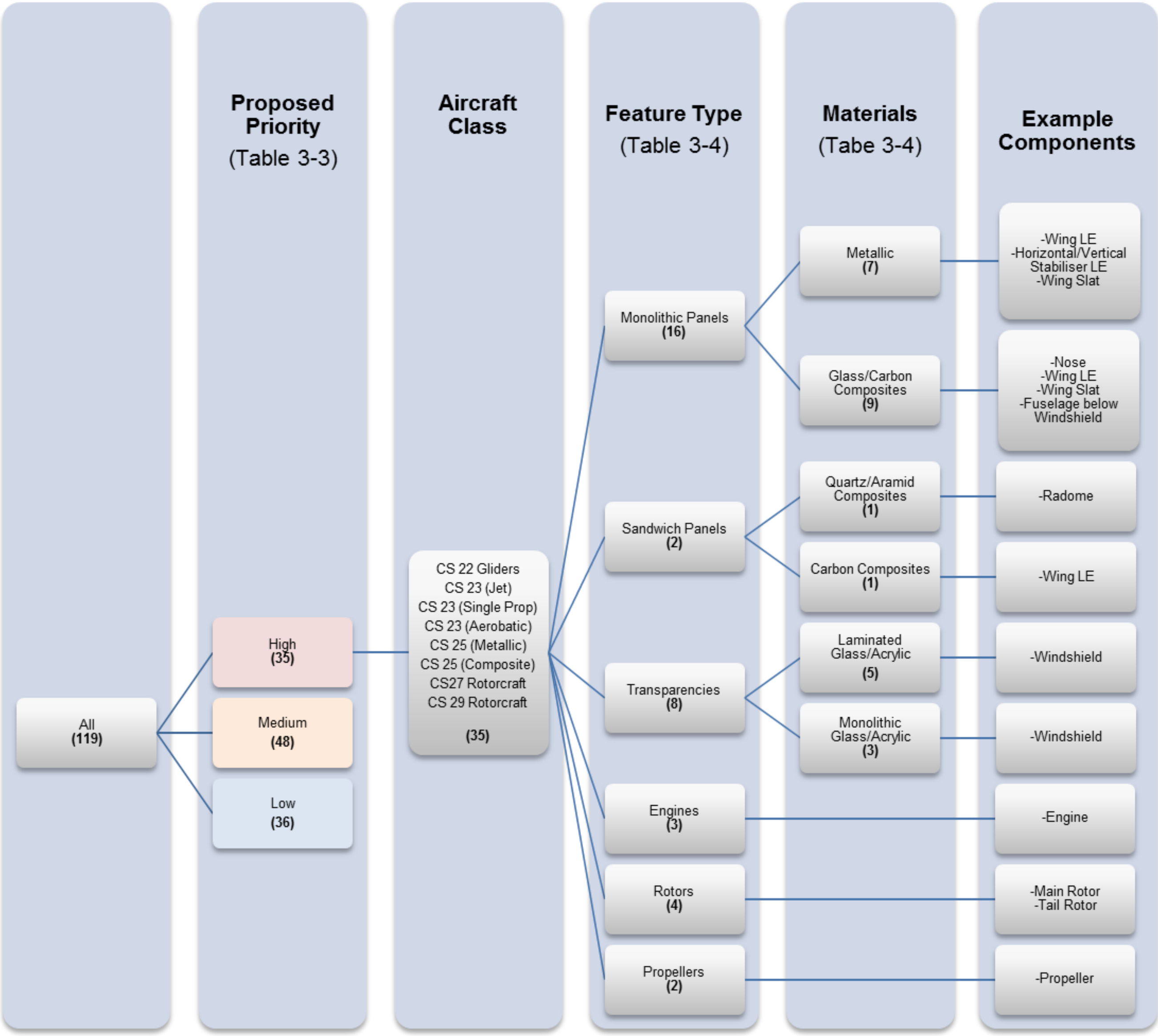


Figure 3-1: Analysis of 'high priority' impact zone data

3.4.2.2 The following observations can be made from this data:

1. The most common 'high priority' feature types are monolithic panels, which can be either metallic (aluminium alloys) or composite (typically GFRP or CFRP).
2. Sandwich panels are also used, though to a lesser extent on forward-facing structures (for the aircraft and features surveyed). However, it is understood that other aircraft within these classes utilise sandwich panels to a greater extent; they have therefore been down-selected as a high priority feature type.
3. Windshields are identified as being high priority for all aircraft types, and are typically laminated constructions for larger aircraft.
4. The remaining high priority components include engines, rotor blades and propellers.

3.4.2.3 During discussion with EASA, concerns were raised that results and priorities could be skewed by the inclusion of the many different classes of General Aviation aircraft. The preliminary results were therefore re-processed to include only CS-23 jets, CS-25 and

CS-29 aircraft, which are relatively large passenger aircraft. The results of this analysis are shown in Figure 3-2.

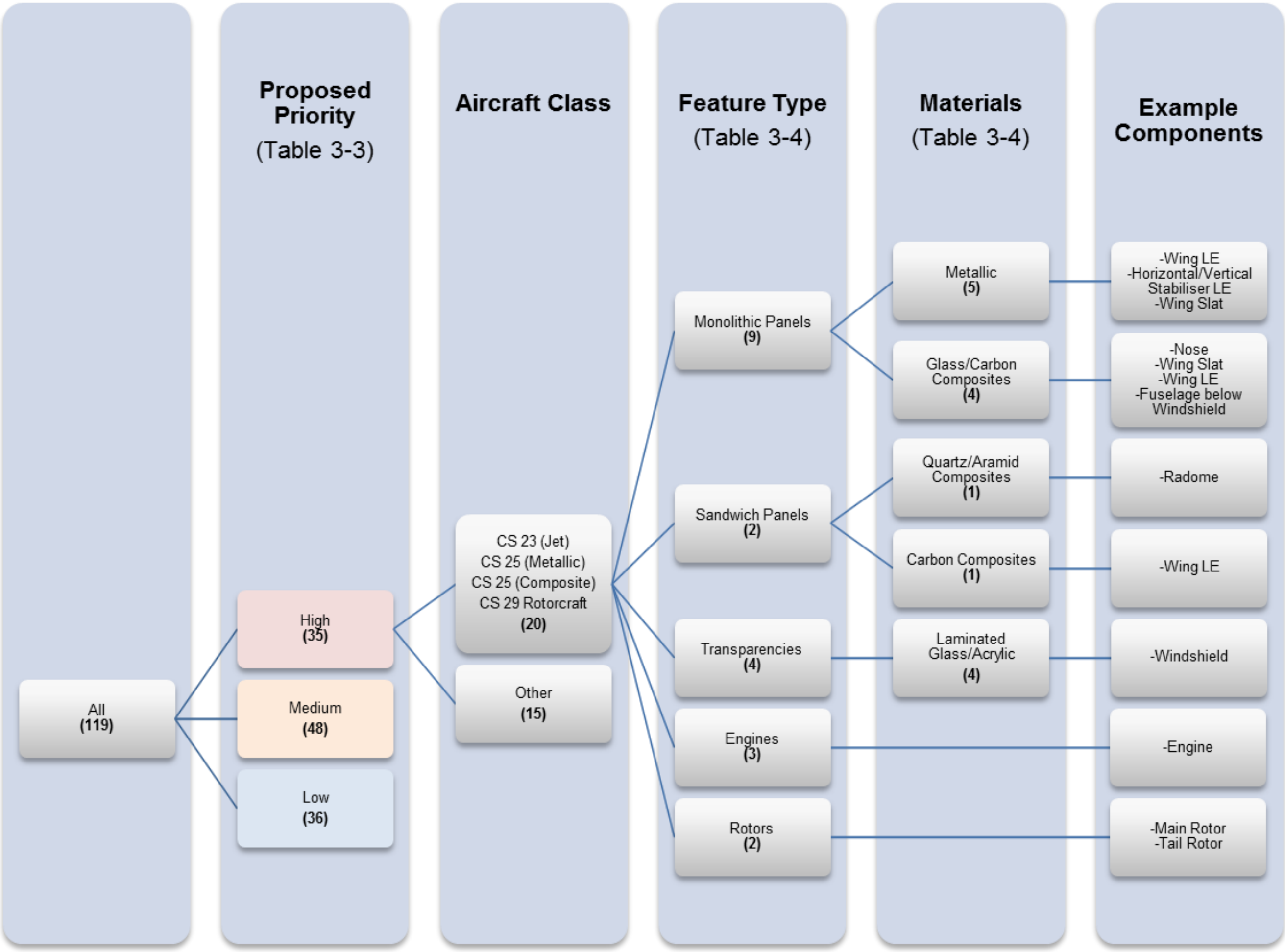


Figure 3-2: Analysis of 'high priority' impact zone data - Filtered for large passenger aircraft

3.4.2.4 It can be seen that although this revised analysis shows slightly different proportions of components against each of the feature/material types, the trends are very similar to those identified against the full set of aircraft types.

3.4.3 Applicability of data to other aircraft classes and lower priority cases

3.4.3.1 The previous section showed how the high priority impact regions that were identified in the spreadsheet survey could be rationalised into a reduced number of feature-based assessments. However, the data obtained against these features would also provide useful data for other regions, including 'medium' and 'low' areas across the different aircraft classes.

3.4.3.2 Assuming that the data generated is applicable to all features within the same structural configuration and material class (either by read-across from test or via validated modelling) then approximately 60% of identified impact locations[11] across all classes of

[11] These are the impact locations identified in paragraph 3.3.7. As identified in Figure 3-1 and Figure 3-2, 119 impact locations have been reviewed across the different classes of aircraft.

aircraft could be evaluated using data from the high priority tests. This reduced to approximately 50% if the high priority tests are designed around only the large passenger aircraft classes (Figure 3-2). The feature type that enables the greatest number of assessments to be made is metallic monolithic stiffened panels, though the majority of these were highlighted as medium priority rather than high.

3.5 Feature-based assessment approach

3.5.1 The process for generating collision data for the down-selected features is outlined here, but is expanded further into proposed research activities in the Work Area 1 report [3].

3.5.2 For all feature types, it is recommended that some element of physical impact testing is required but this should also be supported with FE modelling activities. The testing will provide unequivocal results for a small number of well-controlled scenarios, which can be used to:

- Make Impact Effect Assessments by direct read-across or interpretation of the test results, and;
- Develop and validate FE-based (or analytical) modelling methods that will enable a greater number of impact scenarios to be assesed.

3.5.3 These validated modelling methods can, in turn, be used to explore a greater number of impact scenarios in a cost-effective and timely manner, including:

- Different UAS threat configurations.
- Variations on the panel geometries, including different curvatures and thicknesses.
- Variations of materials within the same material class.
- Variations on impact angle and velocity.
- Providing the ability to develop detailed models of collision scenarios against specific aircraft structures.

3.5.4 As indicated above, the number of variables that could be explored are great, but it is likely that initial activities will need to prioritise high value scenarios whilst applying engineering judgement to account for other factors. This may be patricularly relevant for composite features, where there many permetations of constituent materials, lay-ups, stacking sequences and processing technologies are possible.

3.6 Example feature-based test and modelling activity: ‘Panels’

3.6.1 As an example, the ‘Panels’ feature types includes monolithic and sandwich configurations, using aluminium alloys and composite materials. In these cases, it is proposed that the initial impact testing should be undertaken using a simple, purpose built panel design, such as a curved Leading Edge configuration supported at its chordwise root (representing the spar attachnment) and at its ends (representing riblets). The benefits of using a simplified bespoke specimen design rather than sections of genuine aircraft structure include:

- Avoids logistical difficulties acquiring multiple instances of the same aircraft hardware;
- All specimens will be of known materials and dimensions, with no requirement for detailed structural surveys or proprietary design data;
- All panel specimens can be manufactured to the same nominal design and interfaces, regardless of its material and construction, and;

- Easier interpretation of test results, comparison of modelling predictions, and use for read-across evidence due to simplified construction.

3.6.2 The different panel configurations should be designed, manufactactured and tested using example UAS components[12] e.g. batteries and motors, to determine threshold penetration velocities. Because it typically requires at least three impacts to determine an approximate penetration velocity, it is likely that only a small number of different component/panel combinations would be tested in this way i.e. two or three.

3.6.3 In parallel to these test activities, dynamic ('explicit') FE models of each of the specimens should be developed and impact simulations run using the component Threat Models described in Section 2.5 of Work Area 2.

3.6.4 Results from the impact test activities should be used to guide the development of the FE modelling. Once it can be shown that the FE models are capturing the correct panel deformantion and damage behaviours, they should be run at different impact velocities in order to calculate a penetration velocity threshold that can be compared against the experimental values, along with other observed behaviours.

3.6.5 Subject to a successful validation of the FE models of each panel type, the FE-based studies can be expanded to predict impact behaviours and penetration velocity thresholds for an array of panel designs impacted by whole UAS configurations for each of the four classes (as defined in Work Area 2). Note that this process will involve exploring impact scenarios away from validated test conditions, which increases the technical risk and therefore reduces confidence in results. This would not normally be acceptable for certification purposes but is considered to be appropriate for the purpose of this more-general UAS threat assessment, where the scope of future activities will be constrained by affordibility.

3.6.6 The design of example panels for FE impact modelling can be parametric (such as size scaling or material thicknesses) or could be based upon specific regions of interest on target aircraft. The former avoids the need for proprietary design data (with the potential for associated commercial limitations) and attempts to generate a spread of results against panel configurations that are only loosely based upon example aircraft. The latter provides more accurate results for a limited number of aircraft but at the expense of increased modelling effort per case. For planning purposes, the parametric approach is assumed but this can be revisited at a later date, once it is known what level of aircraft design data will be available to the programme.

3.6.7 These predictions will provide a body of results that can be referenced (without the need for high-end FE software) when required to make informed judgements on abstract collision scenarios involving various classes of UAS and manned aircraft.

3.6.8 The usage of this database of results for Impact Effect Assessments is discussed below in Section 3.7.

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12 The selection of components or whole UAS as projectiles will depend upon the aircraft feature being assessed and also the cost and benefit of testing complete vehicles. Components should be used when impacting small structures e.g. blade leading edges, or when a relatively inexpensive, tightly controlled or less complex collision is required. Whole UAS should be selected when it is important to account for secondary impacts from multiple components or full momentum transfer. In this context, 'whole UAS' may refer to a partial, non-functional UAS representation that only includes the primary threat components.

3.7 Example Impact Effect Assessments: 'Panels'

3.7.1 As part of EASA's Impact & Hazard Effect Assessment (IHEA) process (described further in Section 4), it is necessary to complete an Impact Effect Assessment (level of damage) for each collision scenario of interest. The process for doing this is described below in the context of making assessments of impacts against panels; this is a continuation of the example described above in Section 3.6.

3.7.2 In this example, an IEA is required for a 'Medium' Quadcopter (1.5kg class) impacting the leading edge of a metallic CS-25 empennage structure, with a closing speed of 360 knots (185 m/s).

3.7.3 The first stage of the process is to determine the structural configuration of the impact zone (empennage structure). The next stages should follow a multi-level approach, making best use of available data and low-level methods in preference to expensive or time-consuming assessments in order to reach an acceptably accurate result.

1. **Read-across from similar UAS impact assessments** – *Has an equivalent assessment already been performed for this impact threat and structural configuration?*
2. **Read-across from other Particular Risk certification requirements** – *Can it be shown that the impact threat is enveloped by existing certification tests?*
3. **Read-across from feature-based test results** – This is expected to be the primary assessment method.
4. **Simple analytical models** – *If simple analytical or semi-empirical methods can be shown to be applicable for certain collision scenarios then they may provide an intermediate route to providing an IEA[13].*
5. **Validated FE-based analysis methods** – *If the pre-calculated database of results does not include a sufficiently representative example, or a more detailed assessment of a specific aircraft is required, then the FE modelling methods developed within Works Areas 3 and 4 can be exploited to generate new data. This data would then be included within the database of results to inform future assessments.*
6. **Specific component/sub-assembly testing** – *This represents the 'top of the test pyramid' and would normally only be undertaken when assessing events in which the modelling methods are insufficiently validated or where a high degree of assurance is required.*

3.7.4 For the example, it shall be assumed that a similar UAS impact assessment has not been made which could be referenced i.e. bullet point 1 in multi-level approach. Also, it is assumed that, whilst the bird strike requirement for empennage structures is non-trivial, there is insufficient data to demonstrate that it would envelope this UAS impact requirement.

[13] Methods exist for predicting penetration threshold velocities (typically 'V50' values) for high speed ballistic projectiles, but whole UAS structures are comparatively complex and so are less likely to conform to standard theories without further development. Whilst this option may not prove to be appropriate, it is included at this stage to provoke consideration when processing results in future studies.

Note: 'V50' is the velocity at which 50% of a large sample of identical projectiles will penetrate a given target, acknowledging the probabilistic nature of impact events.

3.7.5 It shall also be assumed that the database of results includes collision results for all four UAS classes (including a ‘Medium’ Quadcopter) against curved monolithic aluminium alloy panels (using appropriate grade such as 2024) that are broadly representative of the example empennage leading edge.

3.7.6 Results would be reviewed for the panels that represent the closest match, including the predicted penetration velocities, damage plots and any accompanying notes. Consideration would be given to how the required impact speed (360 knots) compares with threshold values for the similar examples and judgement would be applied to account for any differences between the actual configuration and the modelled examples.

3.7.7 Based upon this evidence, an IEA rating would be assigned in accordance with the grading defined in EASA’s Task Force report [1] and reproduced in Figure 3-3.

3.7.8 This process, which is illustrated in Figure 3-4, becomes more difficult when the predicted penetration velocities are close to the impact velocity or the structure of interest is significantly different from any pre-calculated examples. Whilst this risk can be mitigated through careful planning of the example configurations, in these cases it may be desirable to expand the dataset with additional FE analysis runs.

Component/Effects	High	Medium	Low
Nose/Radome/Large antennas	Penetration, major deformation, part detachment	No penetration but limited deformation.	Only dents or scratches
fuselage area below windshields	Penetration, major deformation, part detachment	No penetration but limited deformation	Only dents or scratches
Canopy (fuselage area above windshields,)	Penetration, major deformation, part detachment	No penetration but limited deformation	Only dents or scratches
Chin Window (fuselage area below Radome on rotorcraft)	Penetration, major deformation, part detachment	No penetration but limited deformation	Only dents or scratches
Wings (leading edges (including slats), trailing edges (flaps))	Penetration, major deformation, part detachment	No penetration but limited deformation	Only dents or scratches
Winglets	Significant damage, part detachment.	Limited damage, no part detachment	Only dents or scratches
Fairings (e.g. wing to fuselage)	Penetration, major deformation, part detachment	No penetration but limited deformation	Only dents or scratches
Horizontal Stabiliser Leading edge	Penetration, major deformation, part detachment	No penetration but limited deformation	Only dents or scratches
Vertical Stabiliser leading edges	Penetration, major deformation, part detachment	No penetration but limited deformation	Only dents or scratches
Engine pylons, nacelles, air intake cowling	Penetration, major deformation, part detachment	No penetration but limited deformation	Only dents or scratches
Engine (gas turbine)	Significant mechanical damage or detachment of parts. Immediate or ultimate reduction of Engine performance. Significant deterioration of Engine handling characteristics. (see note (*) below)	Non-significant mechanical damage. Reduction of Engine performance, deterioration of Engine handling characteristics and possible Increase of Engine operating temperatures,	No or acceptable damage (as per AMM)
Main & Tail Rotor (blade/hub/controls)	Significant damage resulting in unsustainable rotor unbalance and instability. (Jamming, pitch link breakage or failure, etc.)	Non-significant damage resulting in rotor unbalance within sustainable limits. (Pitch link deformation, etc.)	No or limited damage with no effect on rotor integrity and performance.
Propeller (blades and spinner)	Significant damage resulting in unsustainable propeller unbalance and instability.	Non-significant damage of the blade(s) resulting in propeller unbalance within sustainable limits. No effect on rotor stability.	No effect
Windshield	Penetration or total loss of visibility	No Penetration, partial loss of visibility.	No or limited damage, Non-significant loss of external visibility
Landing gear, and landing gear doors and light	Damage preventing LG safe deployment or affecting essential functions. Total loss of lighting (rotorcraft)	Damage preventing LG safe retraction or other limited damage.	No or limited external damage not affecting operability

Figure 3-3: EASA Impact Effect Assessment guidance, from [1]

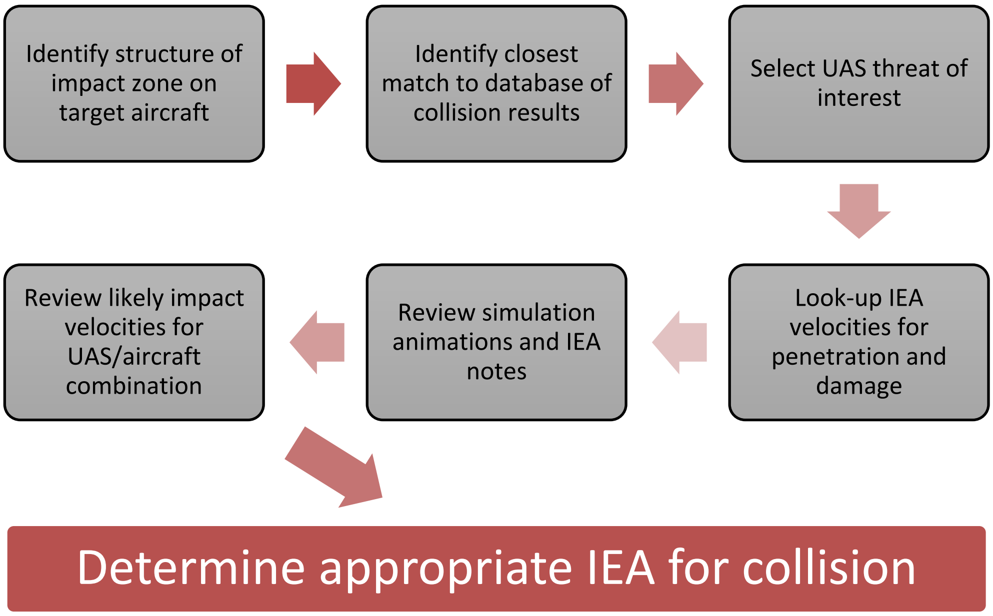

Figure 3-4: Feature based Impact Effect Assessment process diagram

3.8 Recommendations from Work Area 3

3.8.1 The following recommendations are made in order to advance EASA's understanding of UAS impact effects. These are developed upon within Work Area 1, which is reported separately [3]:

1. Near-term collision assessment activities should concentrate upon the high priority features identified within Work Area 3.

2. The design data used for the feature-based analysis should be matured via a more-detailed survey of the identified aircraft components. This might include involvement of the airframe manufacturers or surveys of example aircraft. A family of test specimens should be developed for the purpose of impact testing.

3. An aligned programme of impact testing and Finite Element analysis should be undertaken to provide empirical data and validated analysis methods by which a wide range of impact locations and conditions can be efficiently explored.

4. Validated FE methods should be exploited to expand the initial testing into a database of results for impacts between each of the four UAS class configurations (defined in Work Area 2) and representative aircraft features.

4 Work Area 4: Hazard Effect Classification

4.1 Introduction to Work Area 4

4.1.1 Work Area 2 has matured the definition of the UAS threat and includes recommendations for follow-on activities to develop appropriately detailed Threat Models. Work Area 3 has identified and prioritised impact areas on manned aircraft and proposed an approach by which data and methods can be developed that will enable the effect of impacts to be determined in an efficient manner.

4.1.2 Activities within Work Area 4 are intended to outline how data generated as a result of recommendations from Work Areas 2 and 3 could be used in conjunction with EASA's Impact & Hazard Effect Assessment (IHEA) process, shown in Figure 4-1[14].

4.1.3 Section 4.2 describes the IHEA process and Section 4.3 discusses how the proposed research will align with it. Section 4.4 goes on to reference how IEA are made and Section 4.5 discusses the HEC decision point. Finally, recommendations from the Work Area are made in Section 4.6.

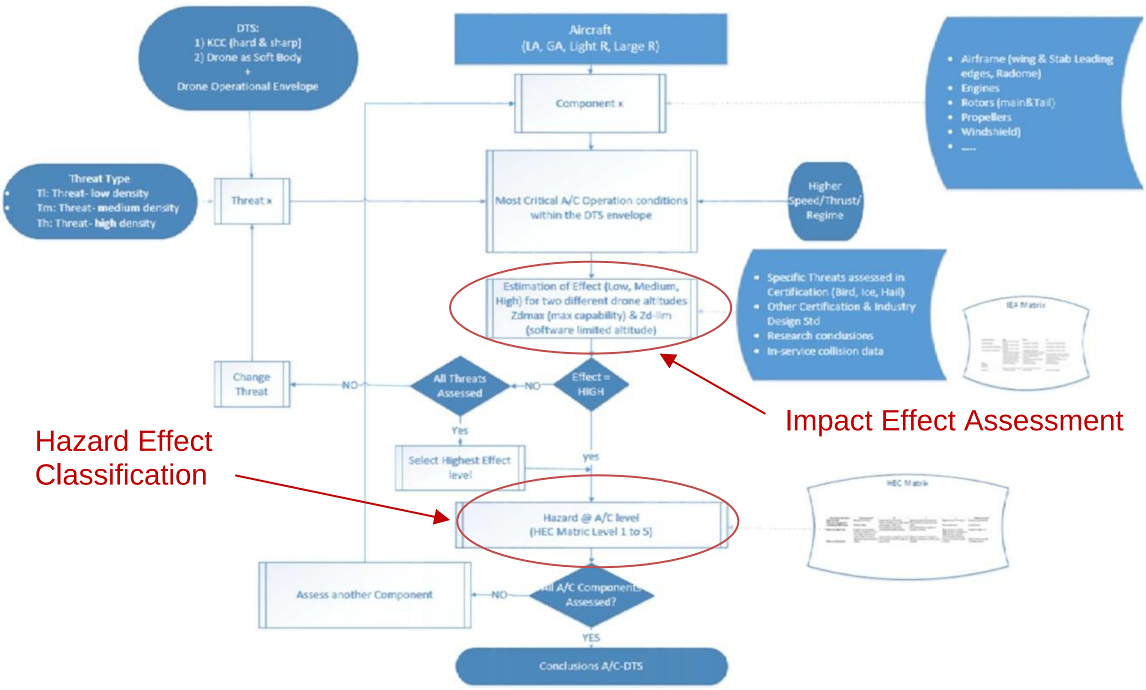

Figure 4-1: EASA Impact & Hazard Effect Assessment process, from [1]

4.2 EASA Impact & Hazard Effect Assessment

4.2.1 The EASA Impact & Hazard Effect Assessment process describes a workflow in which aircraft (or generalised classes of aircraft) are evaluated against UAS threats in order to determine the worst-case credible outcome in the event of a collision.

14 The EASA IHEA process has been reproduced here as a figure to highlight its existence rather than to read in detail. A larger version is available in the EASA Task Force report.

4.2.2 For a given aircraft type, the process involves cycling through each impact zone and making a determination of the Impact Effect (level of damage sustained), assuming worst-case aircraft operating conditions[15]. Where the level of damage is judged to be 'High', as per the EASA Impact Effect Assessment (IEA) definitions shown in Figure 3-3, a further aircraft-level Hazard Effect Classification (HEC) assessment is made. The HEC metrics, which are also defined in [1] and are shown in Figure 4-2, express the outcome of the collision in terms of aircraft safety, rather than damage.

Severity Level	High		Low		
Hazard Classification	**1 (most severe)**	**2**	**3**	**4**	**5 (least severe)**
Effect on A/C	Normally with hull loss	Large reduction in Functional capabilities or safety margins	Significant reduction in Functional capabilities or safety margins	Slight reduction in Functional capabilities or safety margins	No effect on operational capabilities or safety
Effect on Occupants (excluding. Flight Crew)	Multiple fatalities	Serious or fatal injury to a small number of passengers or cabin crew	Physical distress, possibly including injuries	Physical discomfort	Inconvenience
Effect on Flight Crew	Fatalities or incapacitation	Physical distress or excessive workload impairs ability to perform tasks	Physical discomfort or a significant increase in workload	Slight increase in workload	No effect on flight crew
Effect on Operations	Total loss of separation. Total loss of control, mid-air collision, flight into terrain or high speed surface movement collision.	Large reduction in separation or a total loss of air traffic control for a significant period of time	Significant reduction in separation or significant reduction in air traffic control capability.	Slight reduction in separation or slight reduction in air traffic control capability. Significant increase in air traffic controller workload.	Slight increase in air traffic controller workload.

Figure 4-2: EASA Hazard Effect Classification, from [1]

4.3 Aligning research with IHEA process

4.3.1 It is intended that future research activities should be aligned with the basic EASA IHEA process, which provides a systematic approach to making aircraft assessments.

4.3.2 However, although the IHEA process is reasonably well defined, the ability to make accurate and evidence-based assessments of aircraft damage (IEA) across multiple aircraft types, UAS types and impact regions is immature and should be addressed.

4.3.3 The programmes of work outlined in the Work Area 1 report [3] are aimed at providing evidence that will enable IHEA process to be followed, in-line with EASA's requirements.

4.3.4 This is not a trivial requirement as EASA's interests include many classes of aircraft, multiple UAS configurations and many possible impact locations. The permutations are therefore significantly greater than might apply to other, established, Particular Risks

15 Worst-case operating conditions include consideration of two different altitudes, corresponding to software and hardware limits for the relevant UAS. However, as defined in the IHEA process flow chart, only the most critical result will be recorded.

where decades of research and testing have led to reduced sets of impact regions along with their associated threat definitions.

4.3.5 The following guiding requirements were therefore adopted to ensure that the IHEA process could be implemented in a practical and affordable manner:

- **Evidence-based** – Impact Effect Assessments must be substantiated with relevant evidence. This is in contrast to the ‘engineering judgement’-based approach that was necessarily applied by the EASA Task Force and also used in the down-selection of priority features in Work Area 3.
- **Quick** – Looping through the IHEA process must be relatively quick once the initial research has been completed. Although there may be isolated cases where additional levels of assessment are required, the results from research activities should be sufficient to make informed judgements on the majority of high priority impact scenarios.
- **Affordable** – Maximum value must be gained from any research as standard test-based approach on each platform would not be possible.
- **Versatile –** The data generated by future research activities should be applicable to a broad range of impact scenarios e.g. UAS type, aircraft type, impact location, impact velocity etc. This will also enable the effect of potential changes to legislation or operational usage to be evaluated e.g. benefit of enforced UAS altitude limits.
- **Adaptable** – It should be possible to modify or augment the data generated and methods employed to accommodate evolving UAS configurations and usage trends. An example of this might be the ability to account for a new UAS configuration.

4.3.6 These guiding principles have influenced many aspects of this programme, including the down-selection and categorization of high priority aircraft features and the combined use of testing and FE-based analysis.

4.4 Using research output to make Impact Effect Assessments

4.4.1 The decision point in the IHEA process that requires the level of damage to be determined for a given collision is covered by the IEA process. An example of how this would be conducted is given in Section 3.7 and is also discussed within the Work Area 1 report [3].

4.5 Using research output to determine Hazard Effect Classifications

4.5.1 The work that QinetiQ has outlined within this programme is aimed at enabling the level of damage sustained by the manned aircraft due to a collision to be defined, as this represents the gap in knowledge that is specific to UAS collisions. Within the IHEA process, the results of this damage analysis flow into a secondary, aircraft-level hazard assessment that would consider the consequential safety implications. For example, collision damage might be judged to result in one of more of the following consequential threats, each of which could pose a risk to safety:

- Increased crew workload
- Incapacitated pilot/crew
- Reduction/Loss of visibility
- Loss of instrumentation or sensors
- Loss of communications

- Loss of performance
- Reduced control authority
- Unfavourable handling characteristics
- Depressurisation
- Fire
- Unrecoverable loss of control
- Loss of structural integrity
- Damage to landing gear

4.5.2 The severity of these consequential hazards and their probability of developing from the initial collision event would need to consider a wide range of factors, many of which would be unique to the class/model of aircraft and the quality of pilot training. Since these are no longer directly related to the original UAS impact, i.e. they could be due to other failure events, it is assumed that they would be covered within existing, mature hazard assessments or be determined on a case-by-case basis during the IHEA process, with input from suitably qualified aircraft safety specialists.

4.6 Recommendations from Work Area 4

4.6.1 The following recommendations are made in order to develop EASA's IHEA process:

Recommendation WA4-1: Ensure that Hazard Effect Classifications are performed in a consistent manner with input from personnel who are experienced in the test and modelling activities for the IEA and aircraft safety for the HEC.

5 Work Area 5: Risk Assessment

5.1 Introduction to Work Area 5

5.1.1 Work Area 5 focusses on the development of a preliminary hazard analysis using the ‘Bow Tie’ methodology. This activity characterises the interplay between threats, consequences, and barriers/mitigations for airborne conflict between a UAS operating in manned aircraft airspace.

5.2 Bow Tie analysis

5.2.1 The purpose of a qualitative risk assessment is to provide a logical structure of the risk, to demonstrate that risk is being managed to an acceptable level and to facilitate risk management practices.

5.2.2 The basic steps in a risk assessment are to:

1. Identify hazards;
2. Decide who or what may be harmed or damaged, and how this occurs;
3. Assess the risks and take action;
4. Record the findings, and;
5. Review the assessment.

5.2.3 A means to visualise a risk of interest, in a simple picture, is to follow the so-called “Bow Tie” methodology. The output from this process is a diagram that shows a clear differentiation between proactive and reactive risk management. Furthermore, a Bow Tie diagram gives an overview of multiple plausible scenarios, in a single picture.

5.2.4 The following sections define how the Bow Tie is being constructed. This is reflected in the top-level Bow Tie diagram, shown in Figure 5-1. The fully developed Bow Tie diagram is too extensive to be included in the main text and so, is presented over many pages within Appendix A.

5.2.5 Top level event

5.2.5.1 The top level event that forms the basis of this assessment has been defined as ‘*Manned aircraft in collision with a UAS’*.

5.2.5.2 The ‘threats’ are therefore events/situations that might lead to this occurrence and the ‘consequences’ are the effects that a collision might have on the manned aircraft.

5.2.6 Threats

5.2.6.1 In the current model, the ‘threats’ (blue boxes in Figure 5-1) include:

- **UAS misuse**, e.g. due to lack of training, poor visibility, distraction, fatigue, malicious intent.
- **UAS hardware / software fault**, e.g. GPS error.
- **Shared airspace conflict** i.e. where manned aircraft and UAS might be expected to occupy the same airspace.
- **Adverse weather**, e.g. wind exceeding performance of UAS, poor visibility.

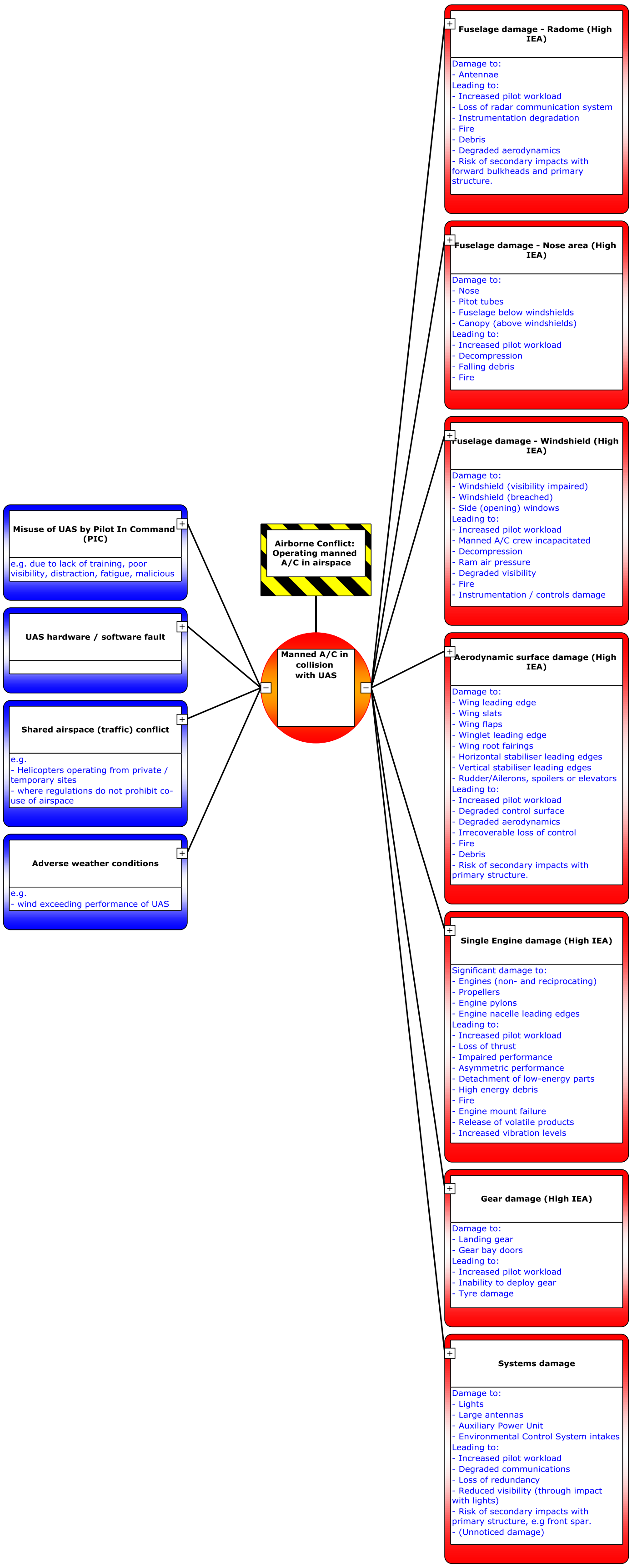

Figure 5-1: Top-level Bow Tie diagram: Manned aircraft collision with UAS

5.2.7 Consequences

5.2.7.1 The ‘consequences’ (red boxes in Figure 5-1) have been expressed in terms of damage to particular zones of the aircraft:

- Fuselage damage – Radome;
- Fuselage damage - Nose area;
- Fuselage damage – Windshield;
- Aerodynamic surface damage;
- Single Engine damage;
- Gear damage;
- Systems damage.

5.2.7.2 The consequences identified in this Bow Tie relate to the level of damage caused to the manned aircraft due to a collision event. However, they do not continue to describe how this damage might result in further injury of loss of life. The justification for structuring the Bow Tie in this manner is that, as presented, all of the data in the Bow Tie is specific to the UAS impact threat and so is directly relevant to this study.

5.2.7.3 The consequences identified by this diagram could be applied as input ‘threats’ for a separate Bow Tie analysis, in which the ability of the aircraft to operate safely would be assessed. Such an assessment would be independent of the cause of damage/failure and might include reference to operating procedures, pilot training and aircraft performance/handling degradation. However, this is likely to be specific each aircraft type and is beyond the scope of this study.

5.2.8 Barriers

5.2.8.1 For each of the threats, a number of barriers have been established which would potentially prevent the top level event occurring; these are shown on the diagram in Appendix A. On the diagram the barriers are colour-coded as follows:

- Green: a potential barrier currently in place;
- Blue: a barrier in regulatory progress;
- Orange: a potential future barrier.

5.2.8.2 As an example, indicated in Figure 5-2, some of the barriers to misuse of the UAS are:

- Existing regulations or Safe Use Apps (green);
- Geofencing or UAS detection by ATCO (blue);
- UAS use restricted to designated areas (orange).

5.2.8.3 Also, for each of the consequences, there are barriers (which are similarly colour-coded) which provide mitigation to high levels of damage (High IEA) after the collision has occurred. These largely relate to the current integrity of the structure being impacted, relying on the existing certification requirements of the aircraft. Potential future mitigations are suggested which relate to UAS design and certification requirements, e.g. frangible airframes, energy-absorbing parts.

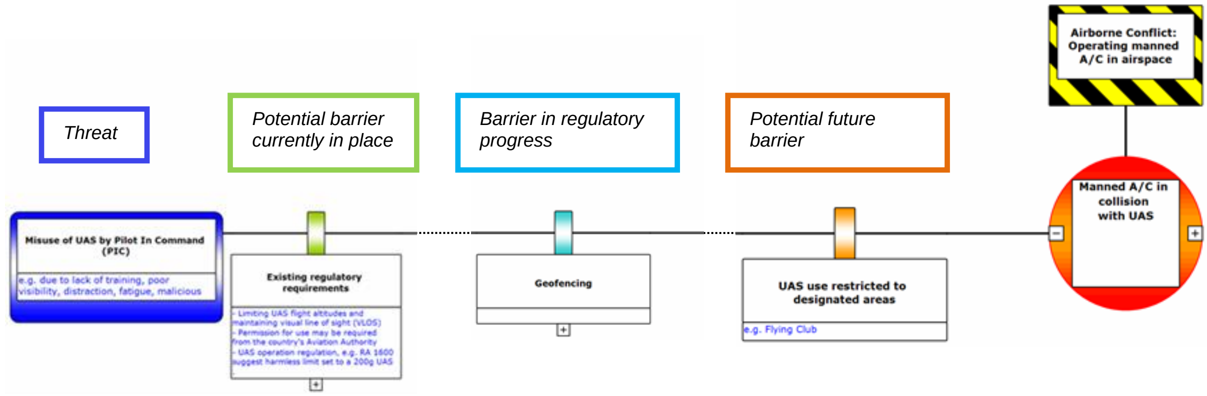

Figure 5-2: Bow Tie diagram: example of barriers to threat of misuse

5.2.9 Escalations

5.2.9.1 Escalations are threats to overcoming the barriers which have been put in place. Some of the established barriers have identified escalations attached to them; this is shown on the diagram in Appendix A.

5.2.9.2 An example is shown in Figure 5-3 for the possible escalations (yellow boxes) to the "existing regulatory requirements" barrier. These include:

- Not all classes of UAS are covered by regulations;
- Regional differences in regulations;
- UAS PIC operating in 'risky manner';
- UAS PIC unaware of legal obligations;
- UAS PIC aware but accidental incursion;
- Ambiguity of regulations.

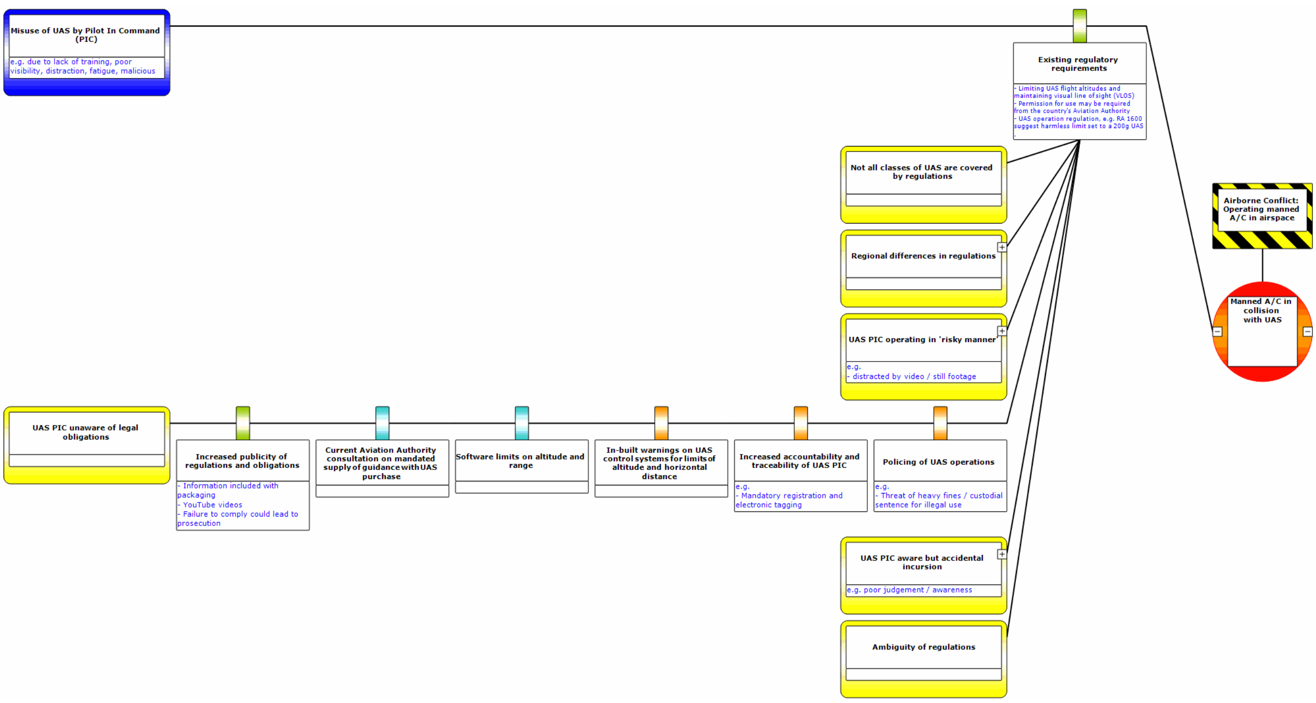

Figure 5-3: Bow Tie diagram: example of escalations to the existing regulations barrier

5.2.9.3 As the escalations are essentially threats, further barriers can be put in place, specifically against the escalations. This is illustrated in Figure 5-3 for one of the escalations, with the barriers color-coded as previously described. All of the identified escalations and their barriers are shown on the diagram in Appendix A.

5.3 Recommendations from Work Area 5

Recommendation WA5-1: A statistical analysis of the velocity vs altitude of manned aircraft of different classes is recommended. This will:

- Enable flight velocities to be calculated (to an agreed statistical basis) at different altitudes for each class of aircraft so that collision speeds can be determined and the potential benefits of limiting UAS altitudes can be quantified. Note that this data will also be valuable for bird strike assessments.
- Provide evidence to aid the management of UAS collision risks.

6 References

1. *'Drone Collision' Task Force - Final Report*, EASA, 04/10/2016.
2. *Research programme on collisions with UASs*, EASA, EASA.2016.LVP.50, Oct 2016.
3. Bill Austen, *Research Programme on Collisions with Drones: Work Area 1 Report*, QinetiQ, QINETIQ/17/01933, July 2017.
4. David Bush, *Detailed Project Plan (D1) Research Programme on Collisions with UASs - Version 1*, QinetiQ, QINETIQ/17/00621, 15th February 2017.
5. *eCalc*https://www.ecalc.ch/, March 2017.

7 List of Abbreviations

A/C *or* a/c	Aircraft
BVID	Barely Visible Impact Damage
COTS	Commercial Off-The-Shelf
CS	Certification Specification
EASA	European Aviation Safety Agency
ESC	Electronic Speed Controller
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Model
FPV	First-Person View
FRP	Fibre Reinforced Plastic
HEC	Hazard Effect Classification
IEA	Impact Effect Assessment
LiFePO	Lithium Iron Phosphate (battery)
LiPo	Lithium Polymer (battery)
MAC	Mid-Air Collision
NATS	National Air Traffic Control Services
OEM	Original Equipment Manufacturer
PIC	Pilot In Command
PR	Particular Risk
RPAS	Remotely Piloted Air System
RPM	Revolutions Per Minute
UAS	Unmanned Aircraft System
VLOS	Visual Line Of Sight
WA	Work Area
WP	Work Package

A BowTie Methodology

A.1 This appendix details the BowTie methodology developed as part of WA5.

A.2 The methodology focusses on the development of a preliminary hazard analysis to characterise the interplay between threats, consequences, and barriers/mitigations for airborne conflict between a UAS operating in manned aircraft airspace.

A.3 The following pages present the various levels of the methodology:

- Top level event with Threats and Consequences
    - Barriers to Threats and Consequences
    - Barriers to Threats:
        - Misuse of UAS: Escalations to Barriers
        - Hardware/Software fault: Escalations to Barriers
        - Airspace conflict: Escalations to Barriers
        - Adverse weather: Escalations to Barriers
    - Barriers to Consequences
        - Fuselage damage: Escalations to Barriers

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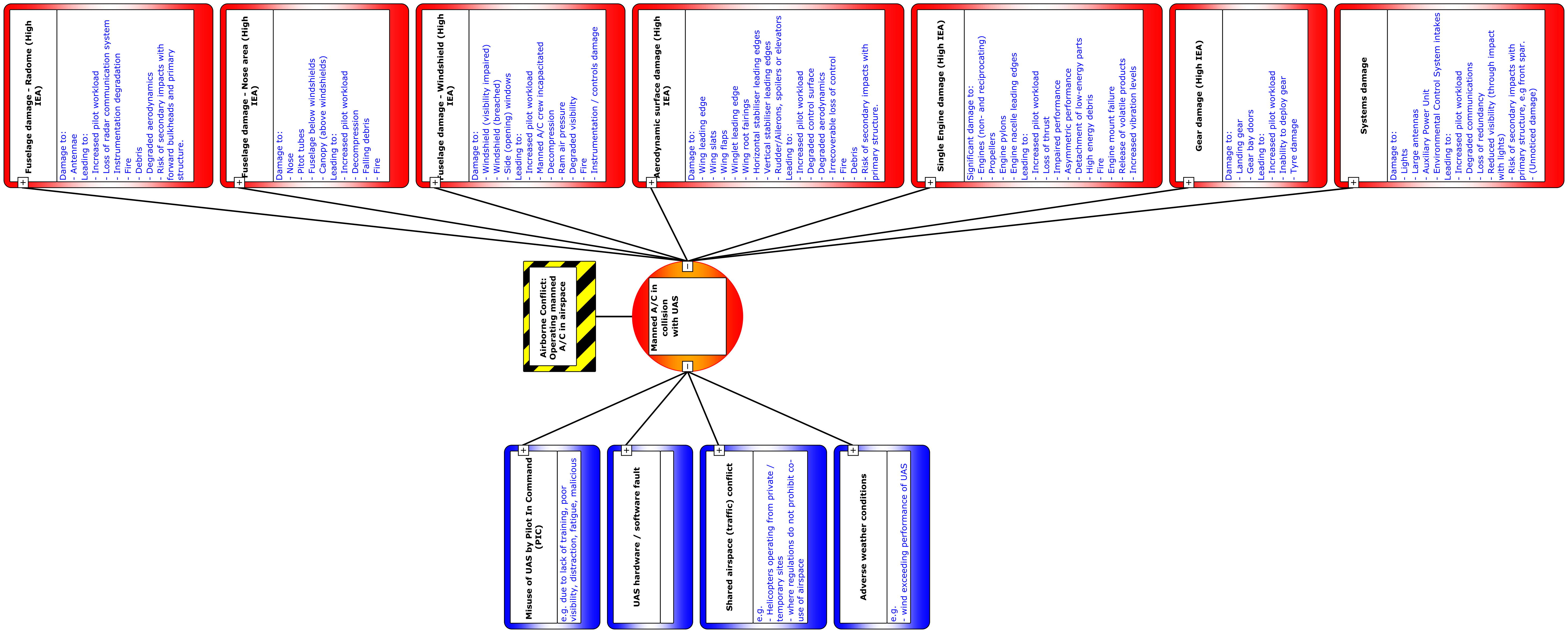
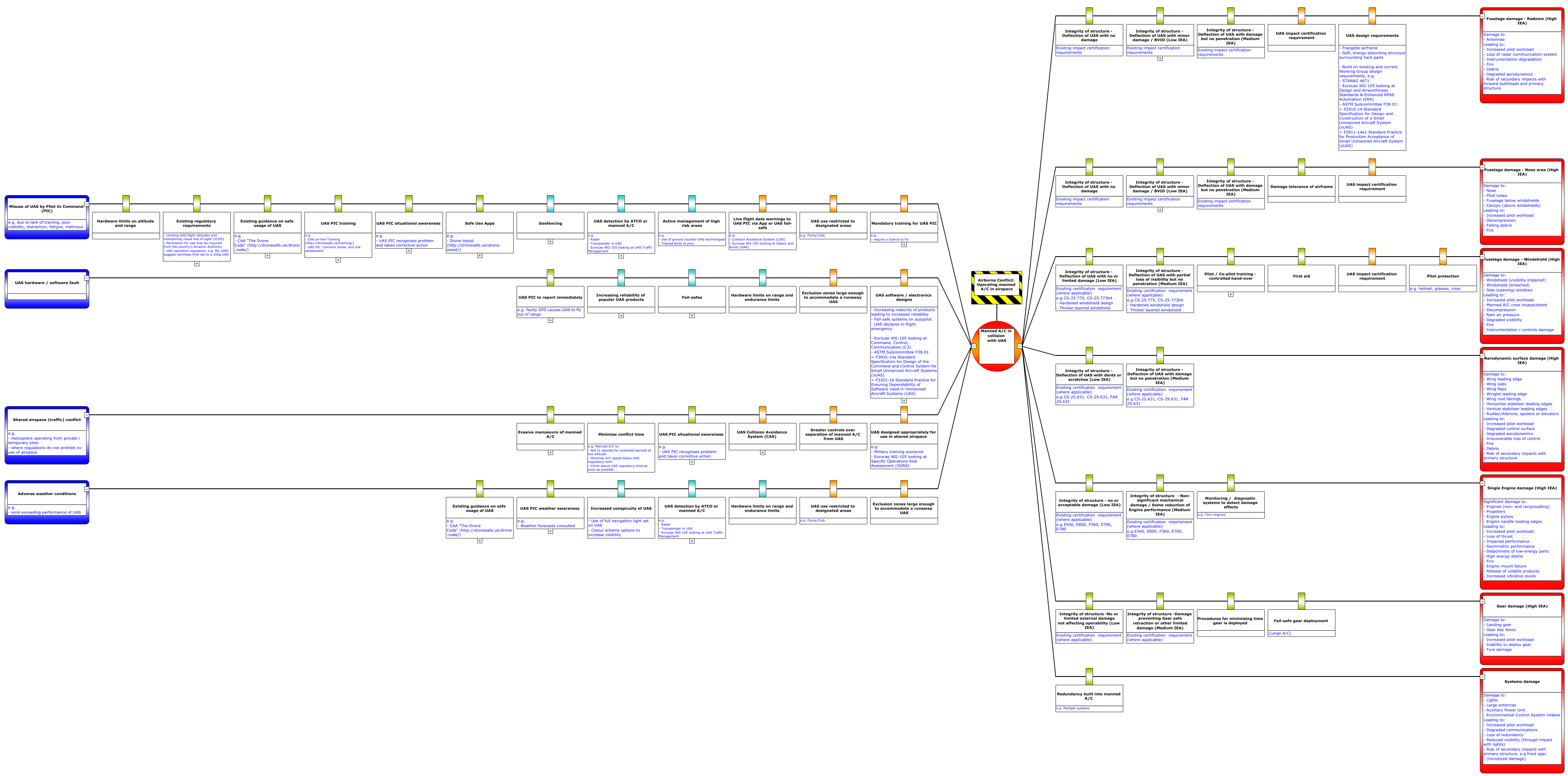
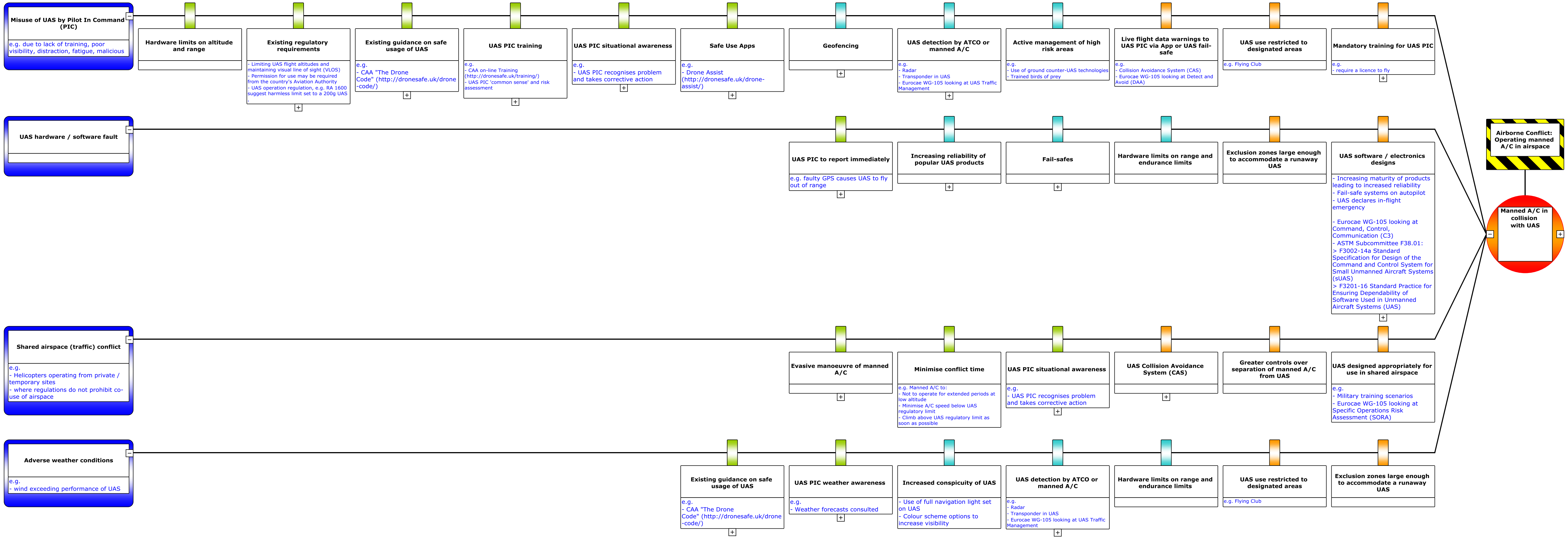


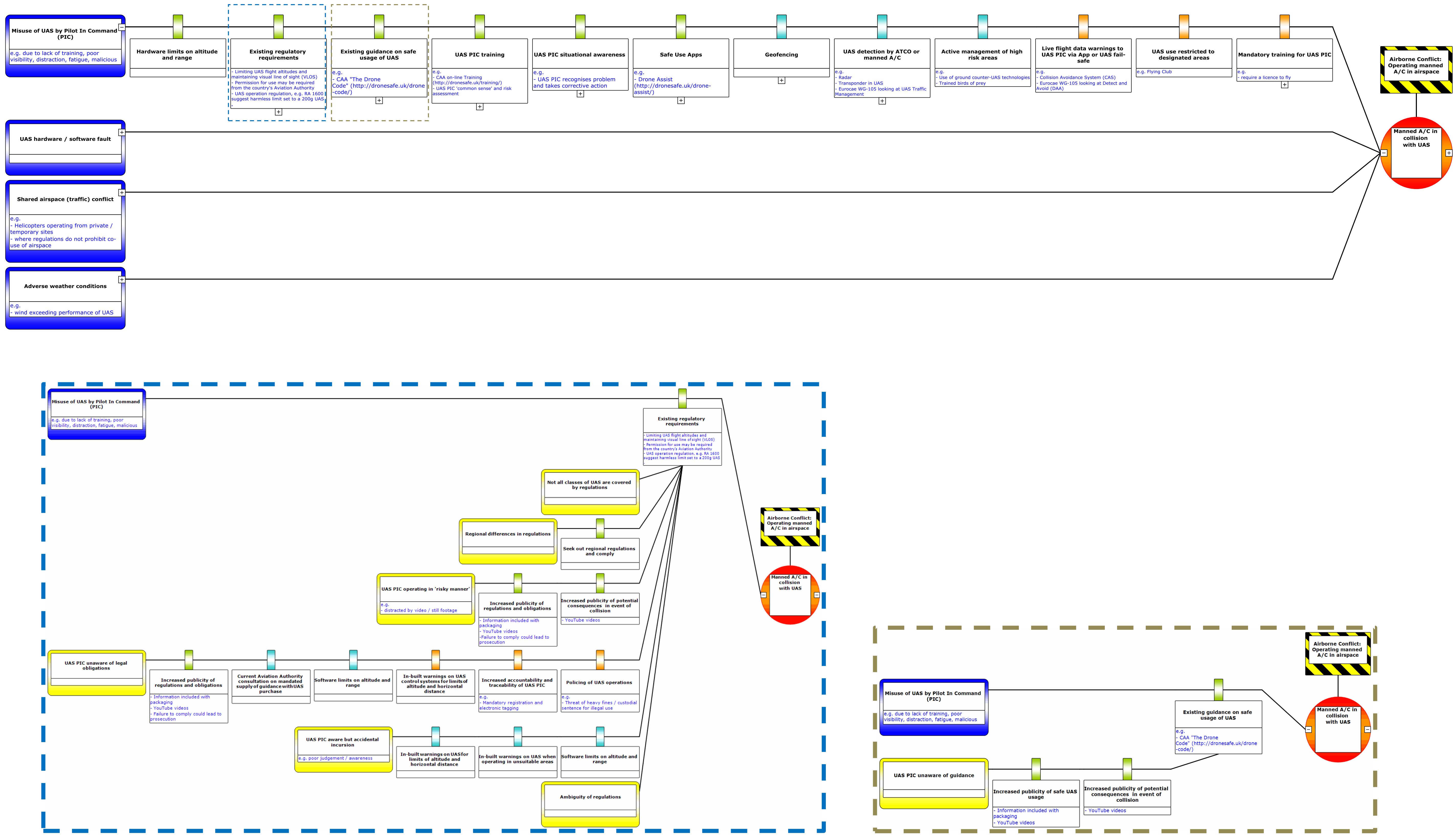
Top Level event with Threats and Consequences



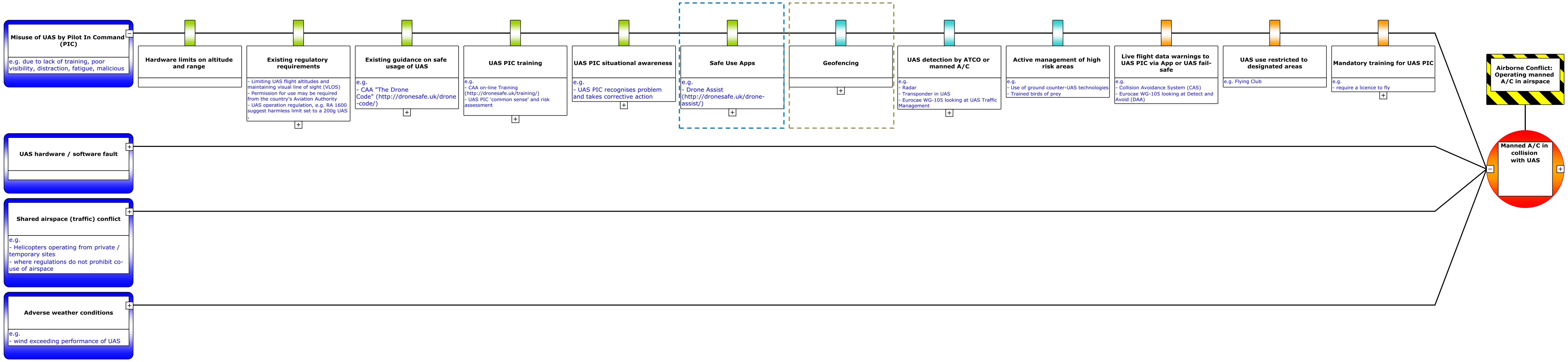
Barriers to Threats and Consequences

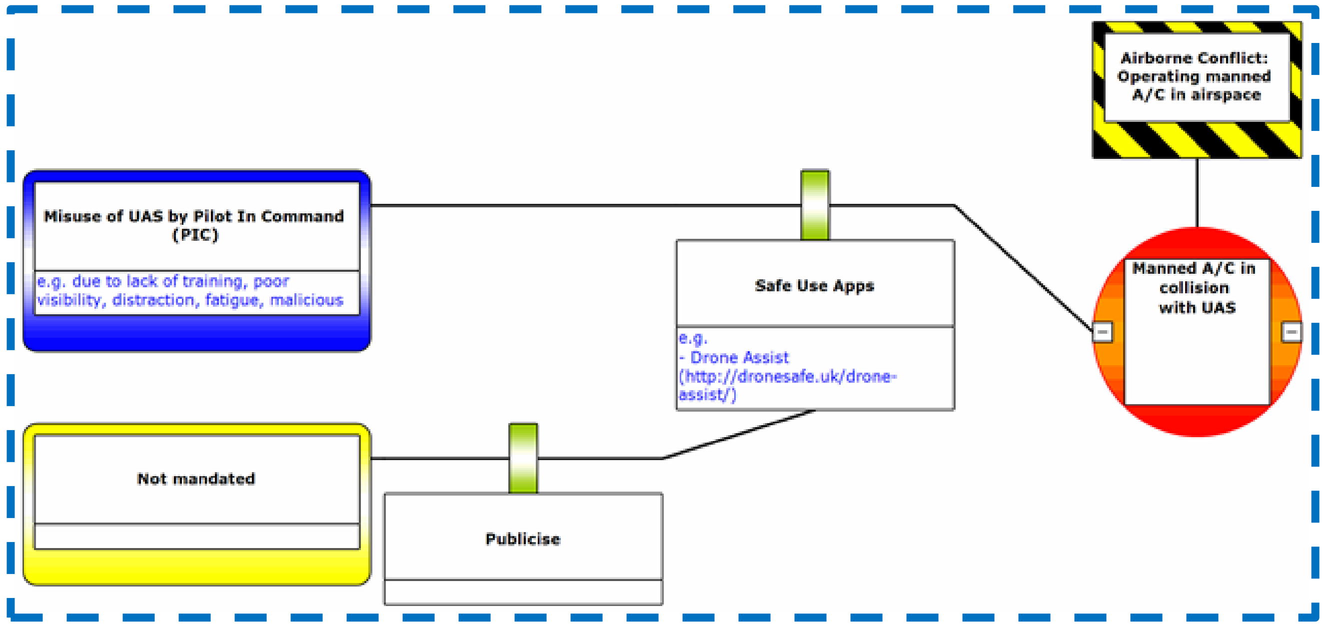


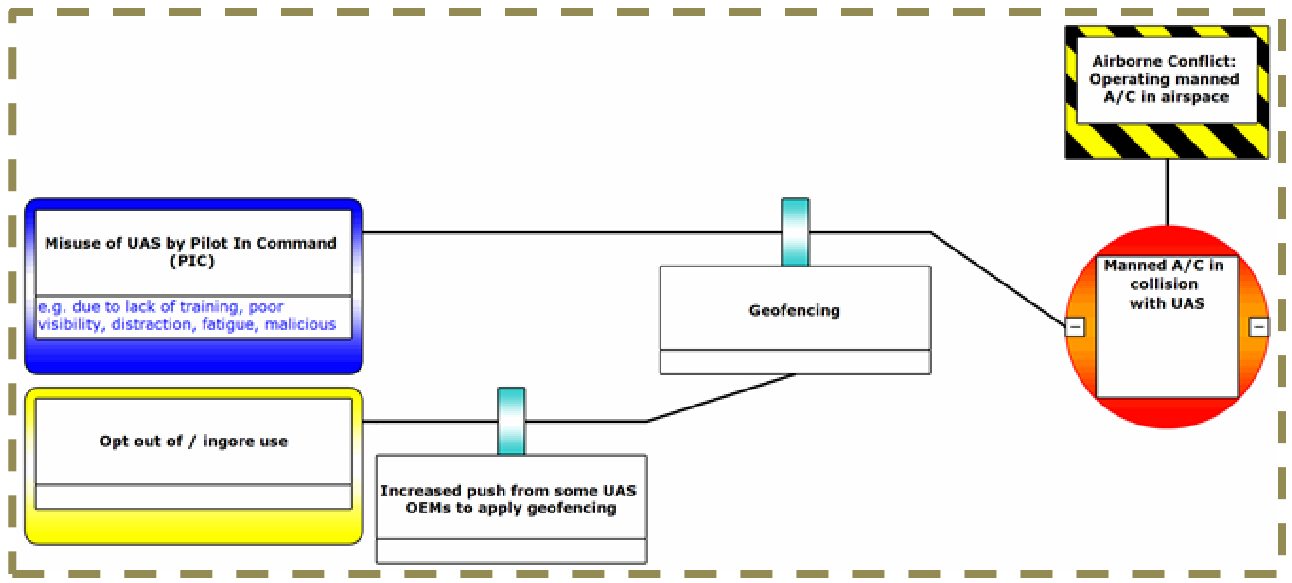
Barriers to Threats



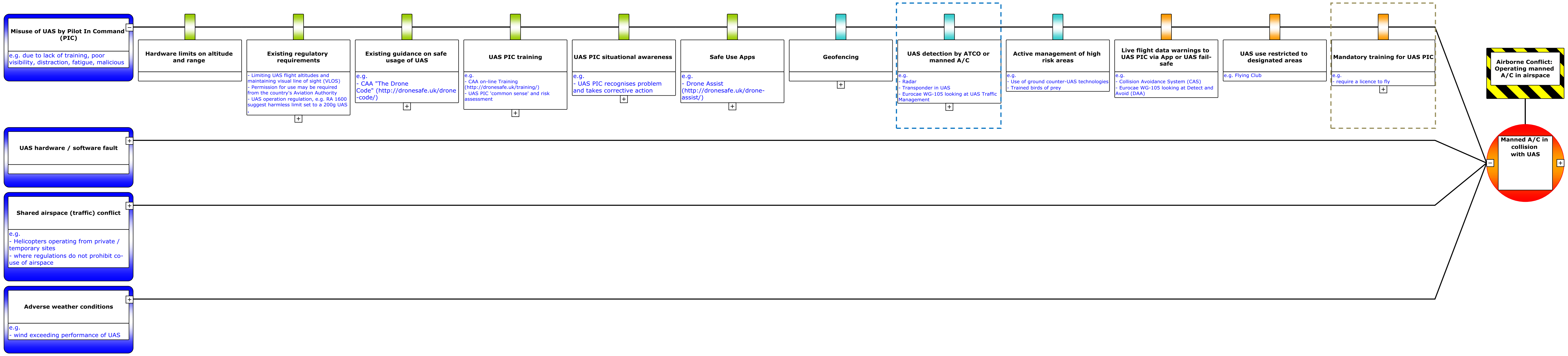
Misuse of UAS:
Escalations to Barriers

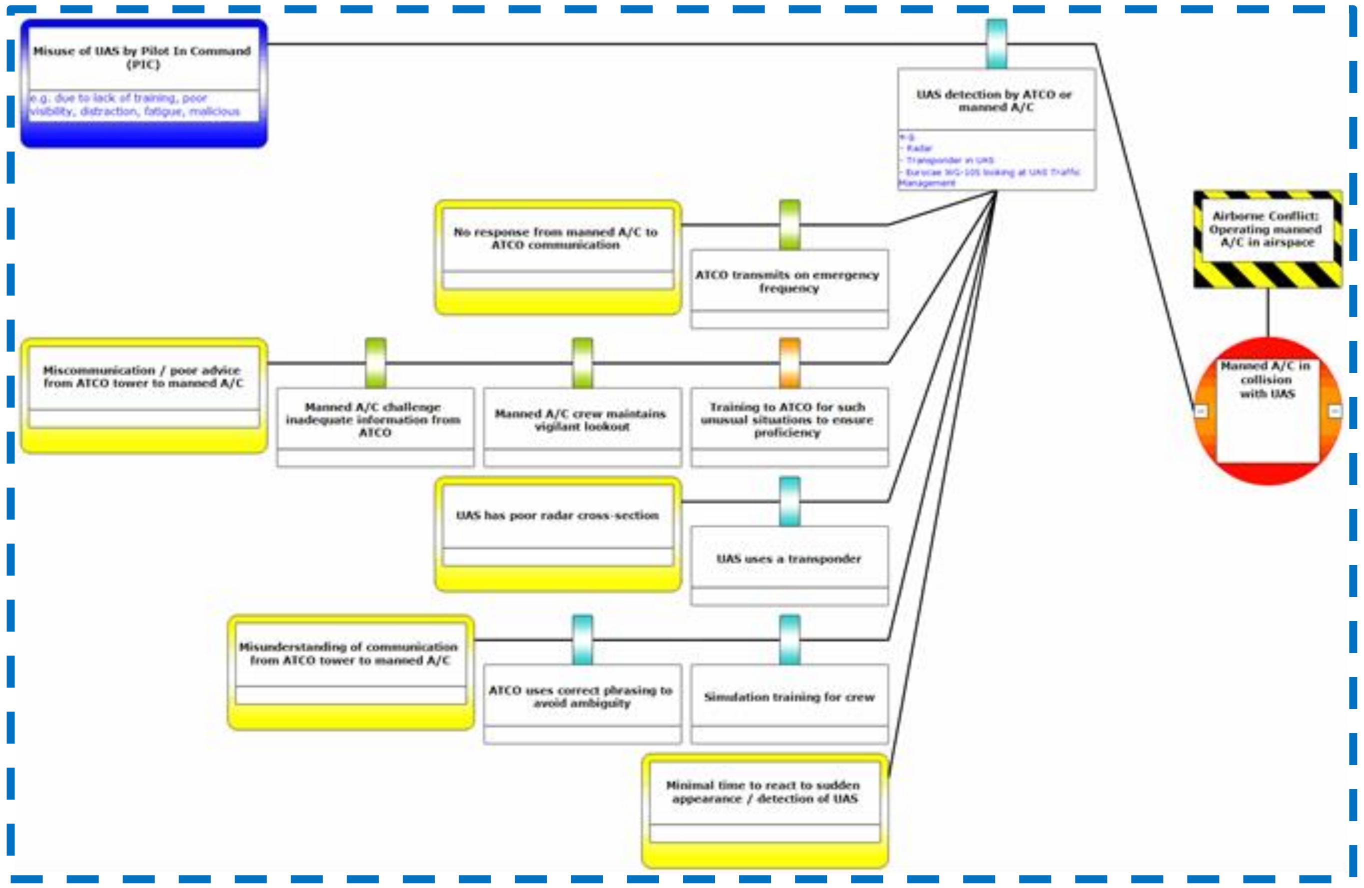


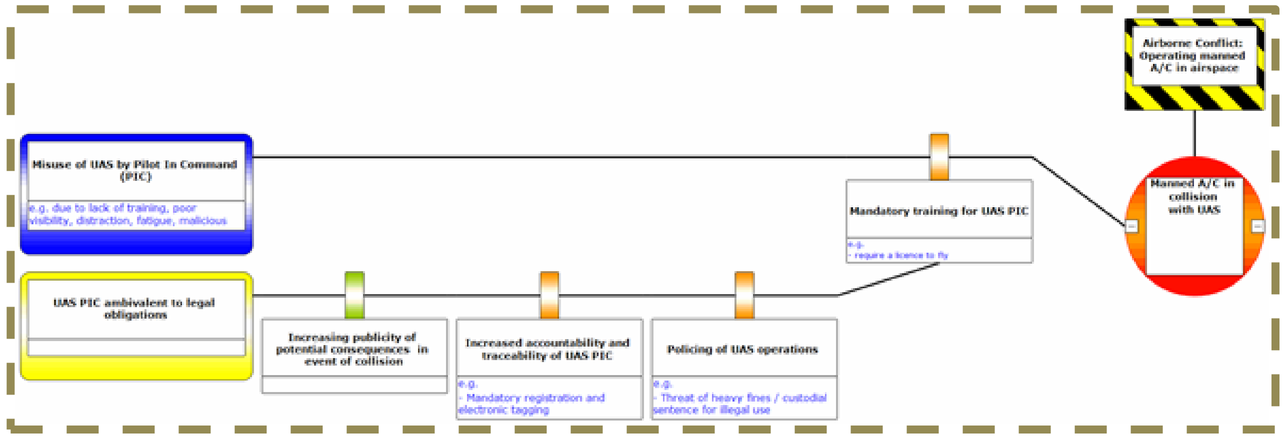




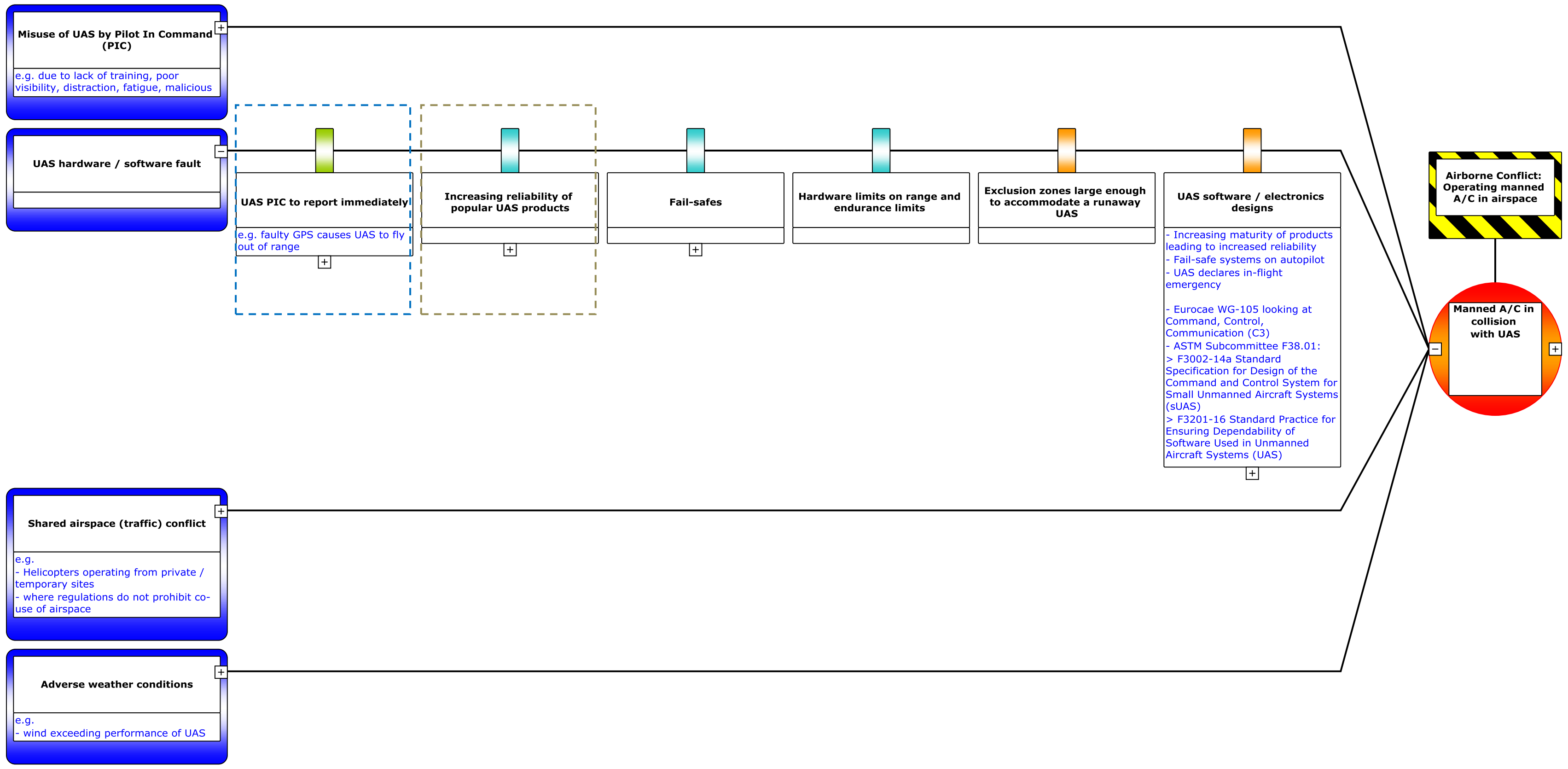
Misuse of UAS: Escalations to Barriers

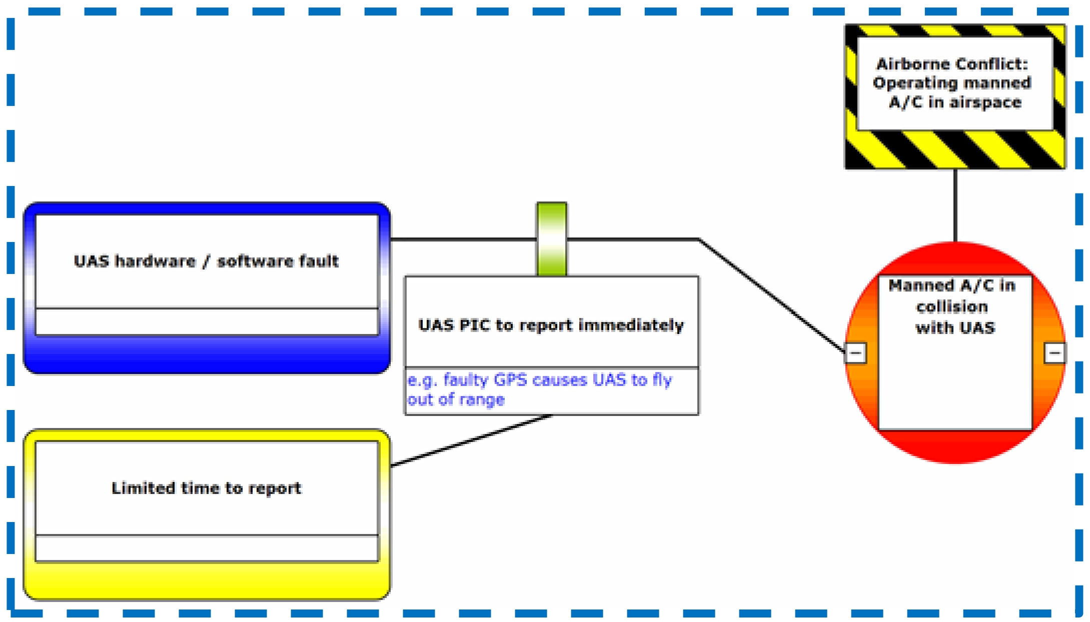


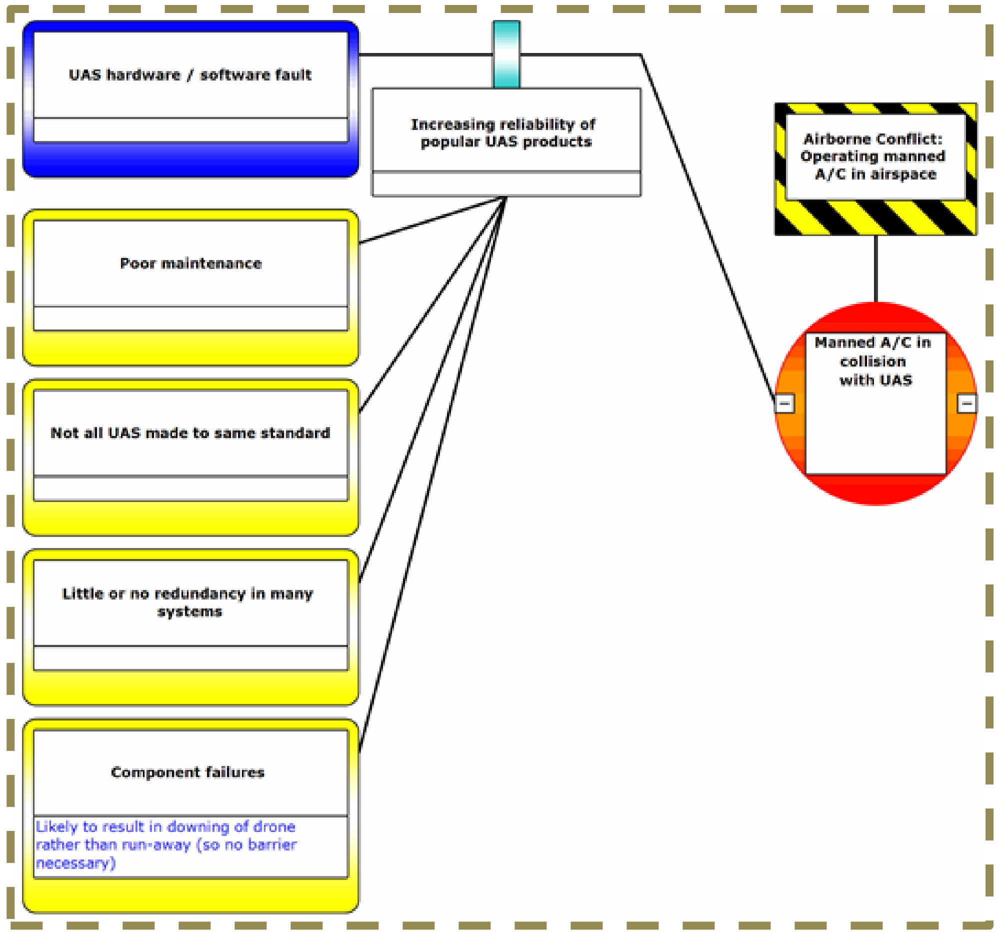




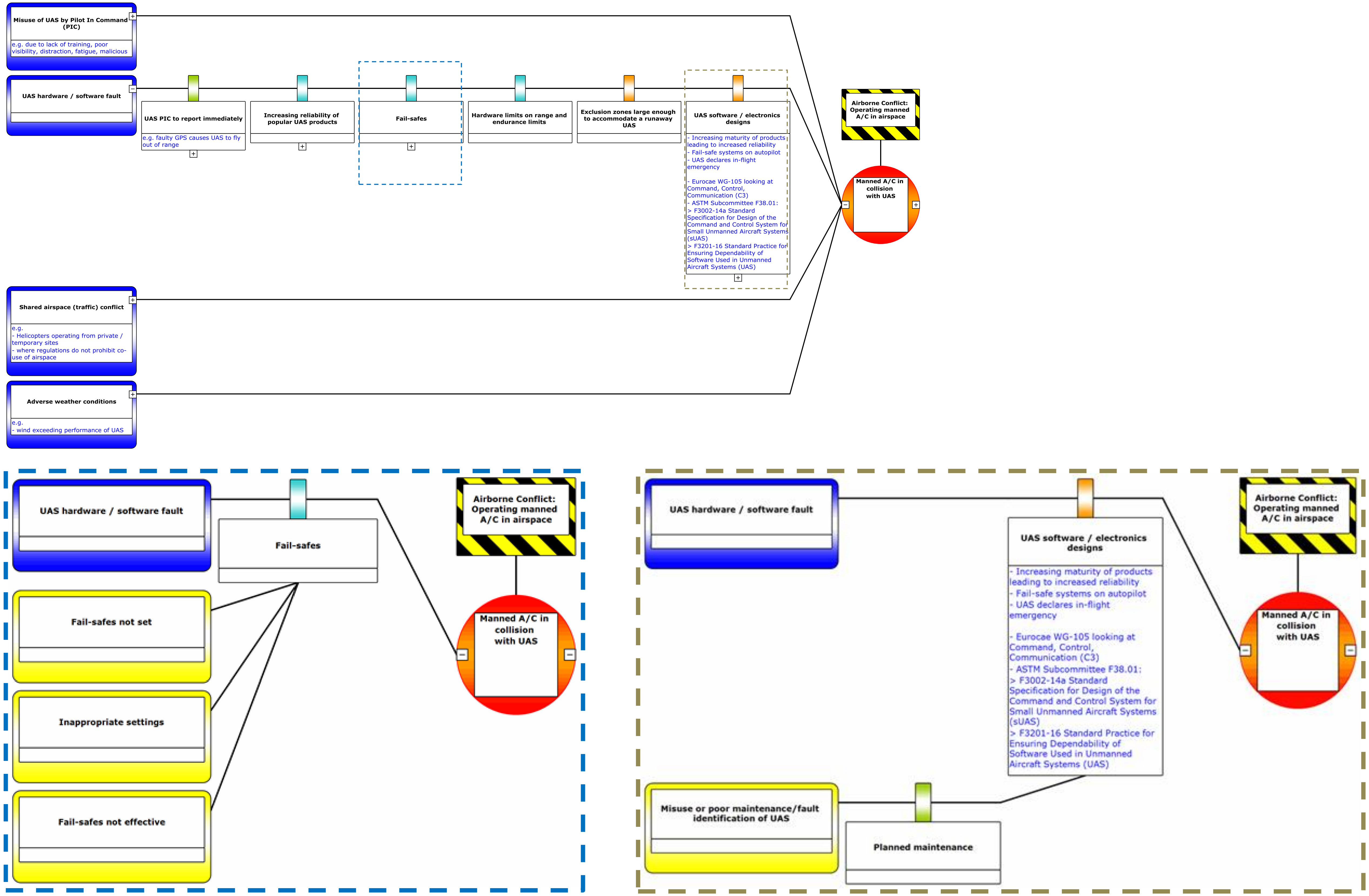
**Misuse of UAS:
Escalations to Barriers**



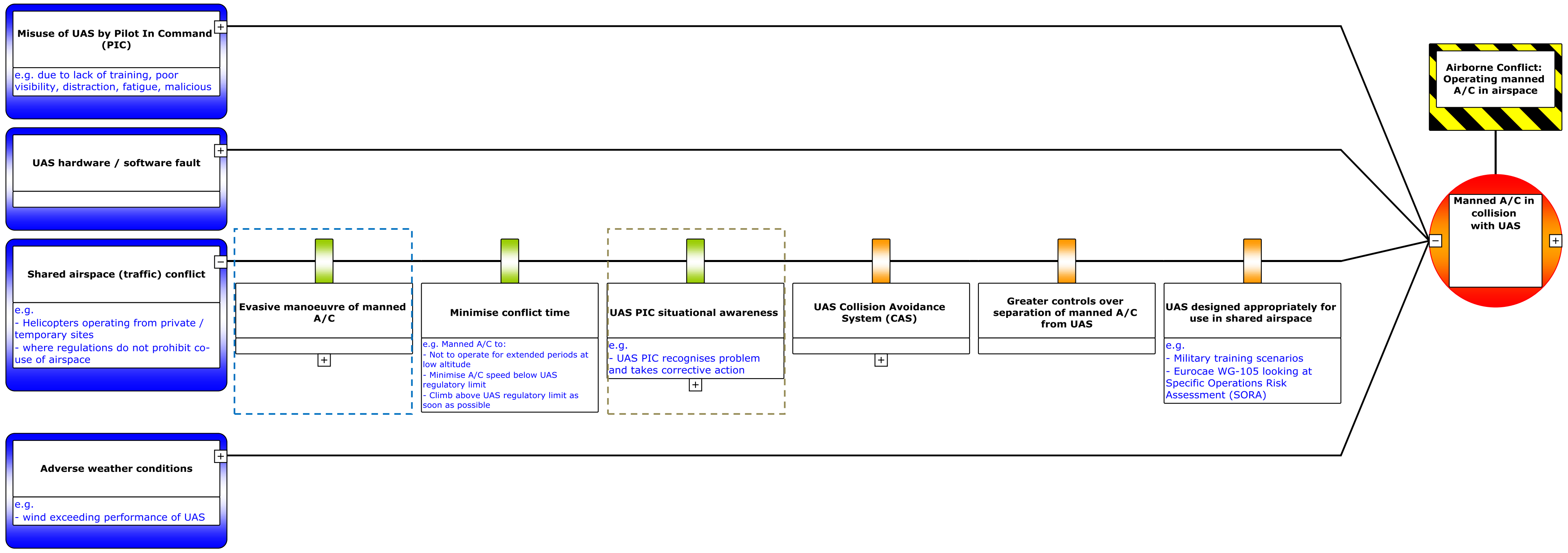


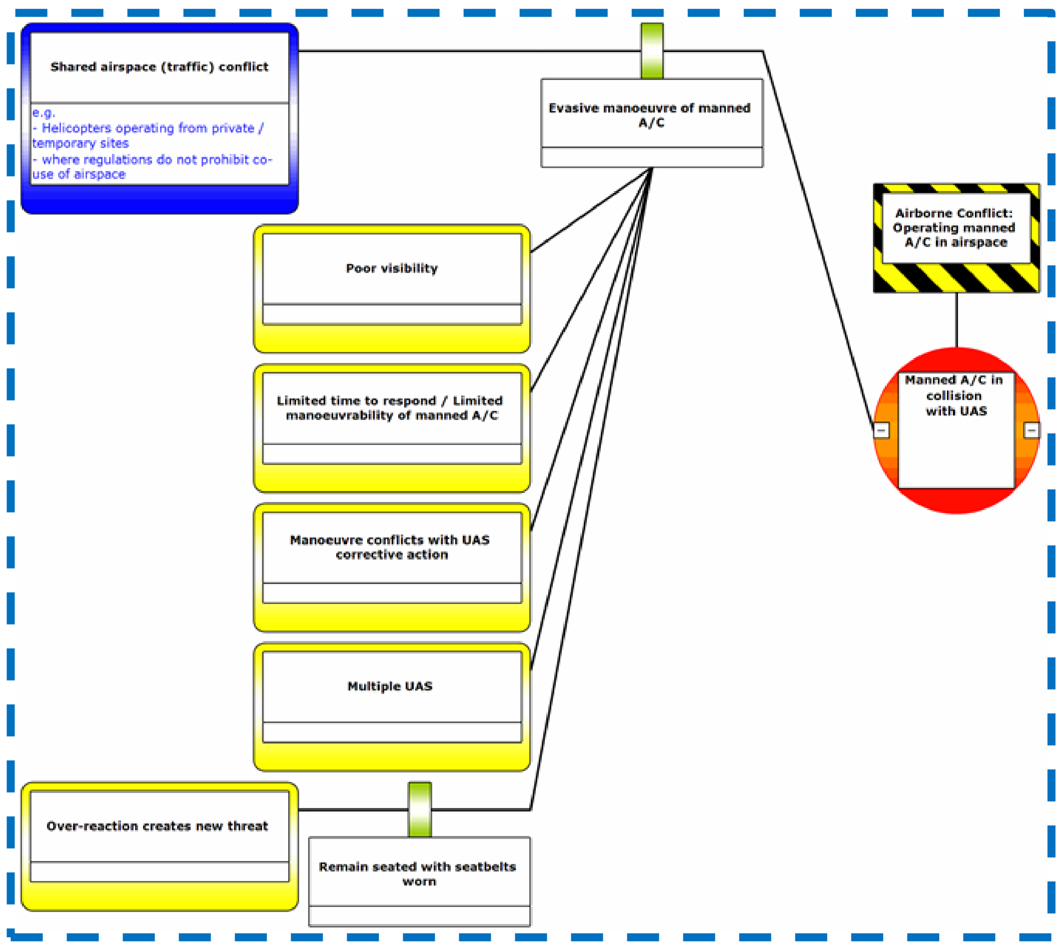


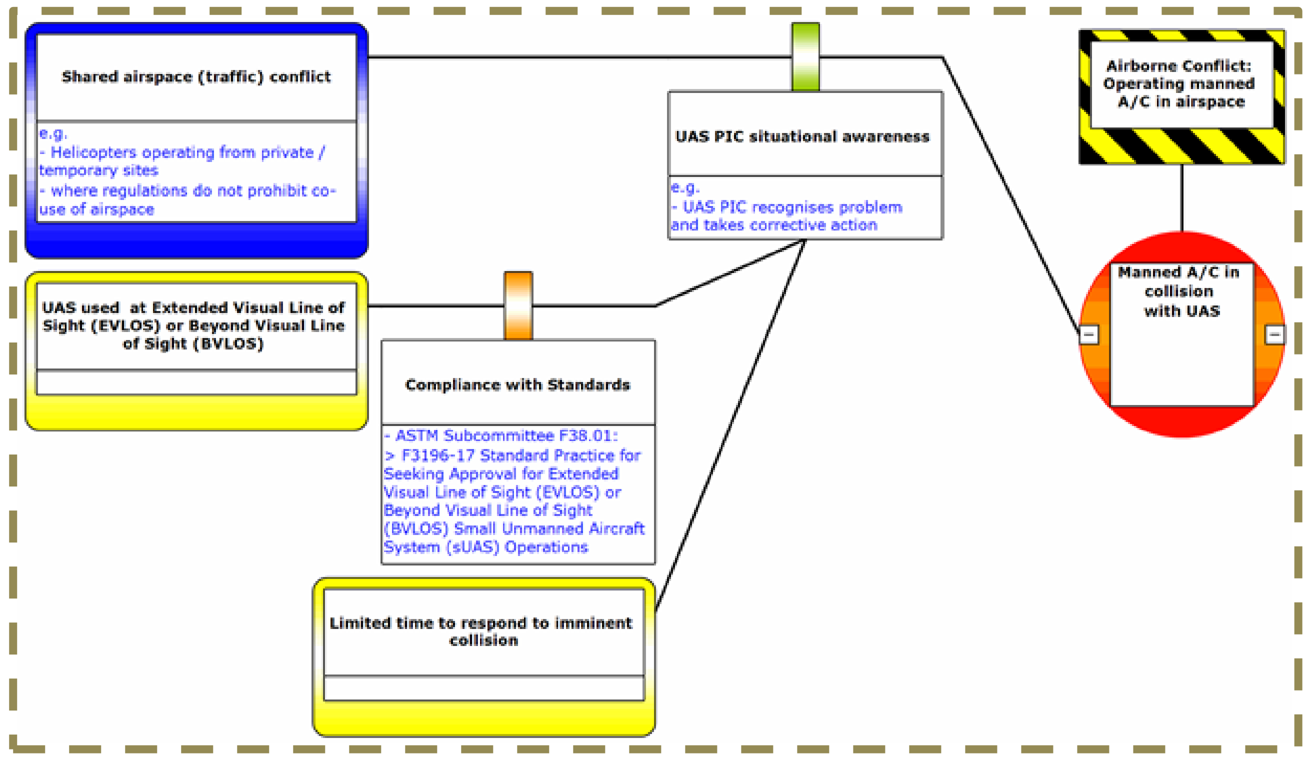
Hardware/Software faults: Escalations to Barriers



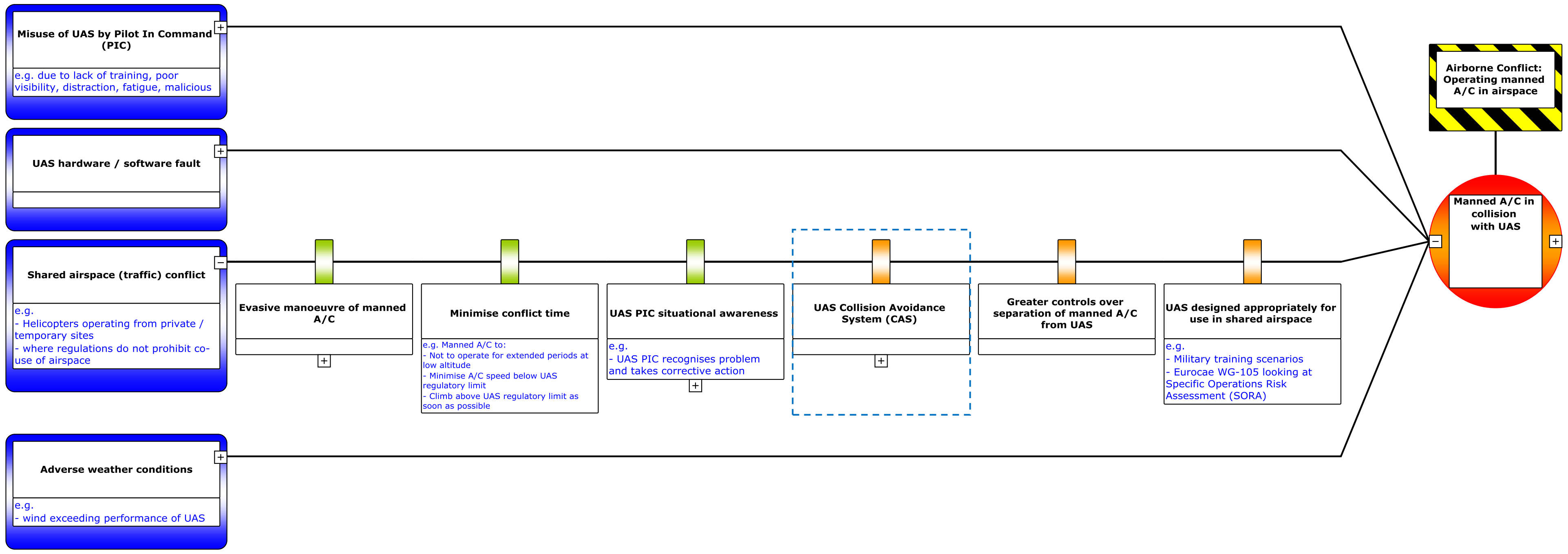
Hardware/Software faults: Escalations to Barriers

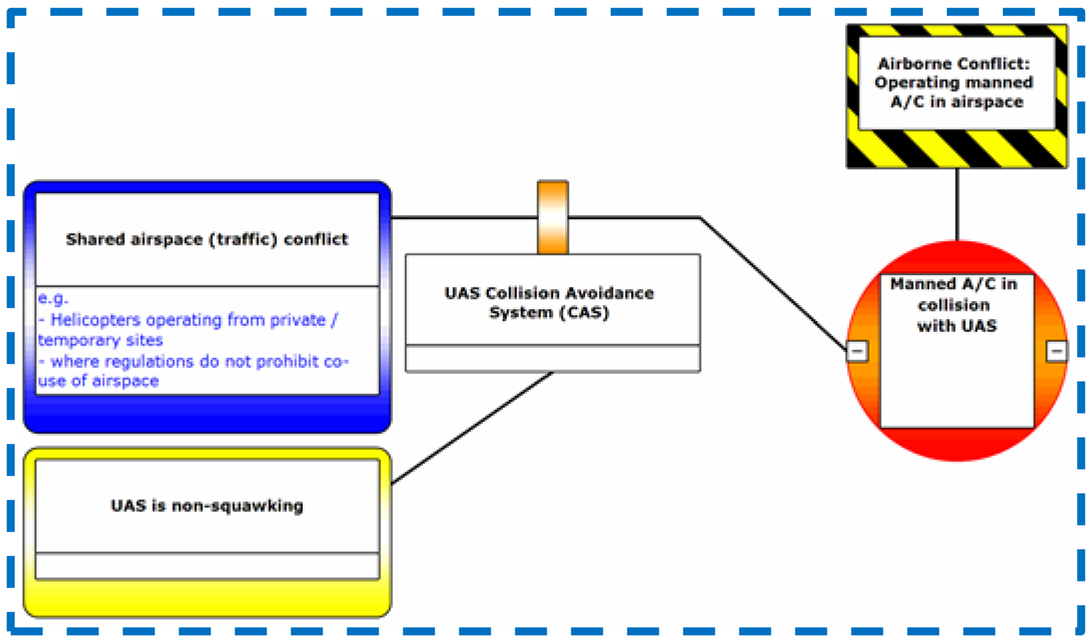




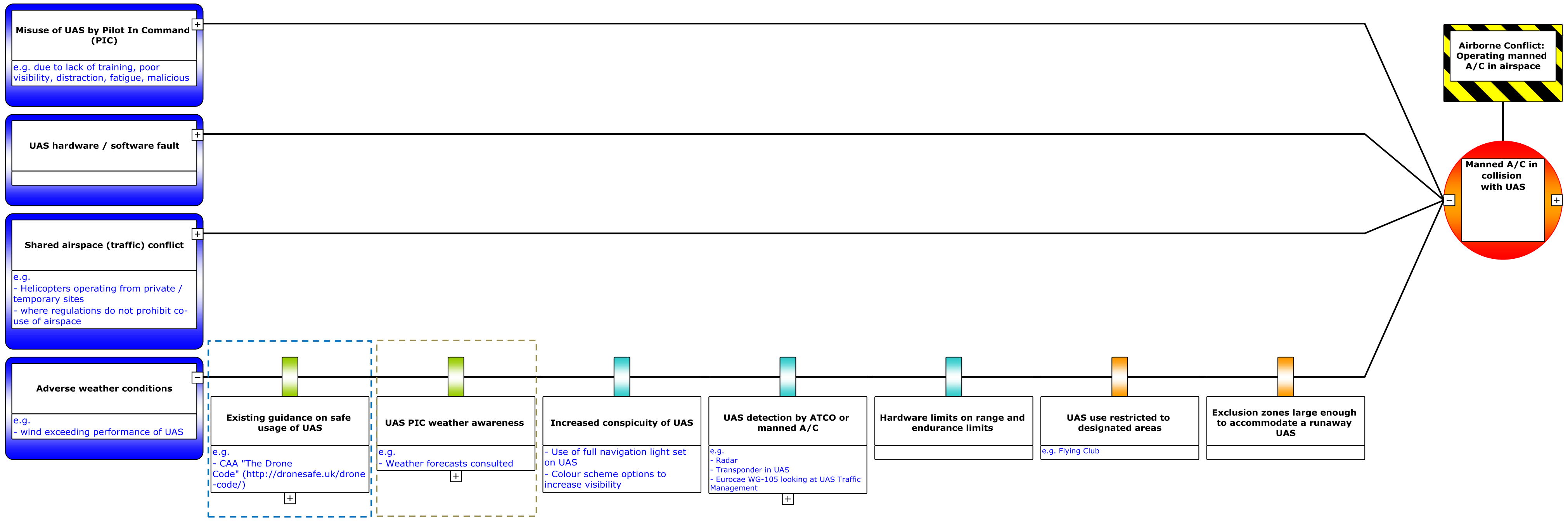


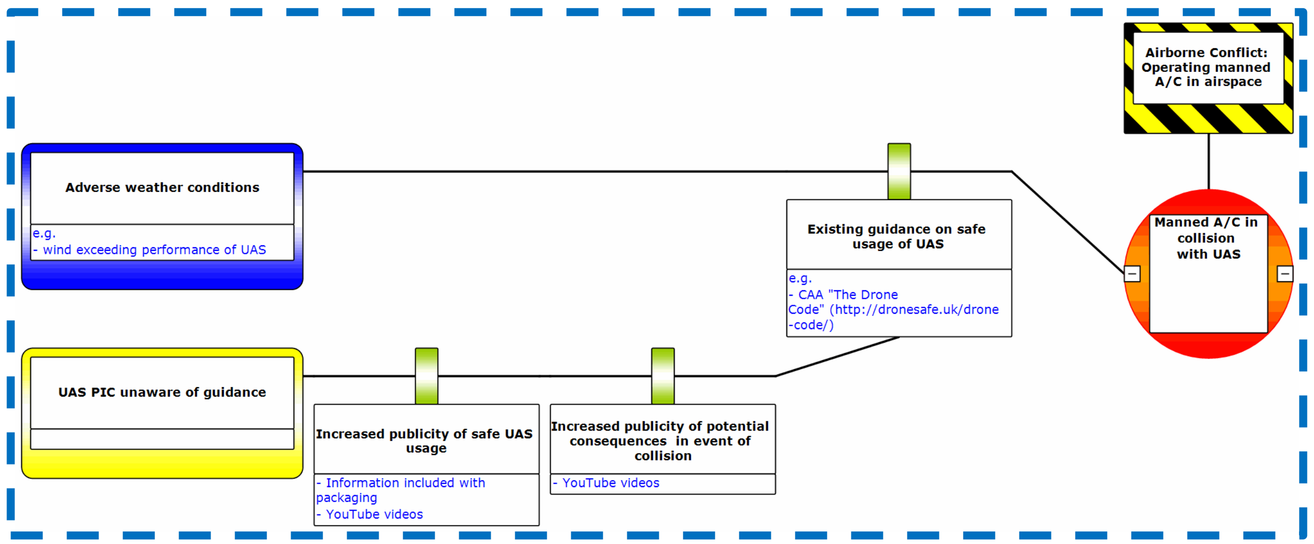
Conflict airspace: Escalations to Barriers

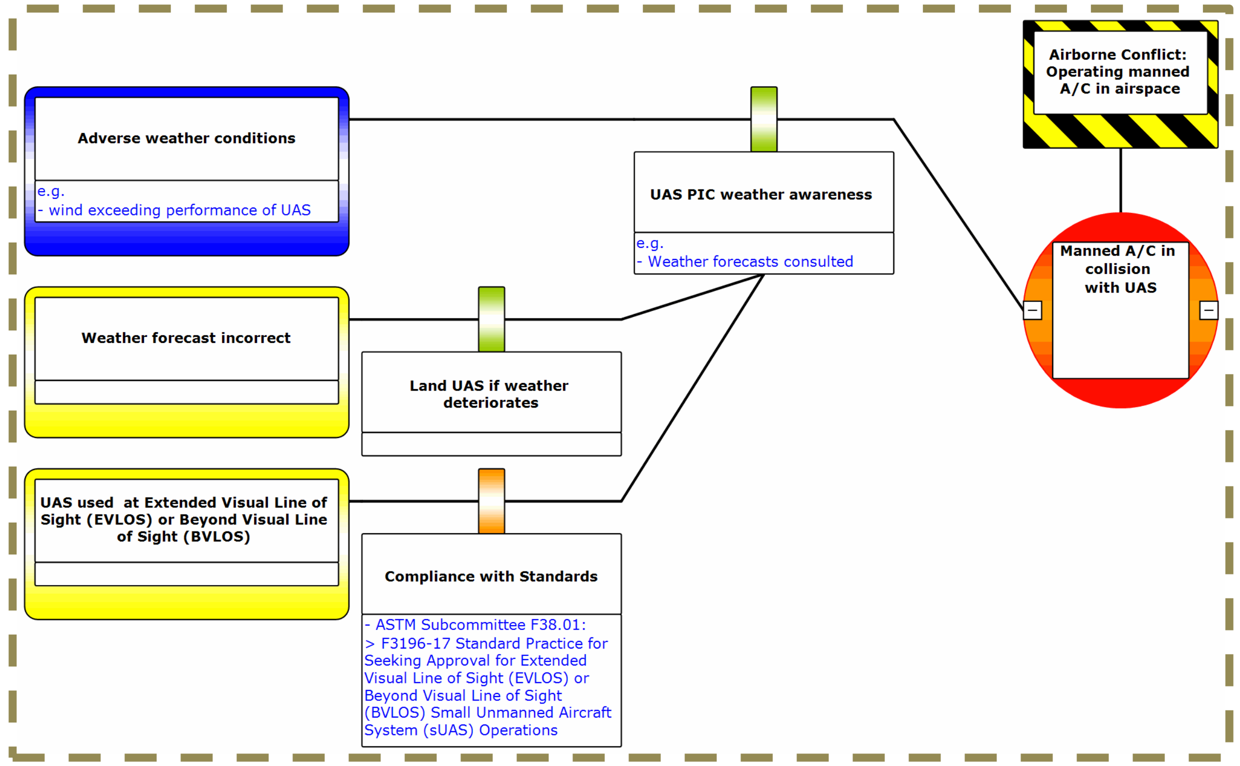




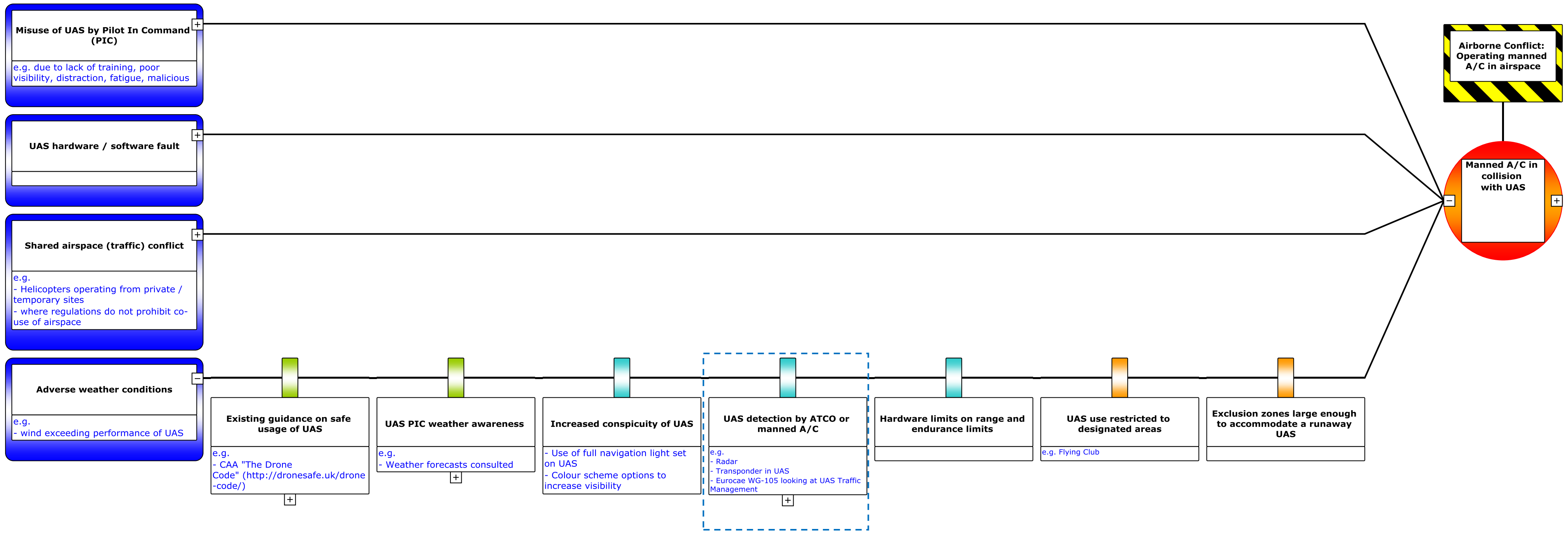
Conflict airspace:
Escalations to Barriers

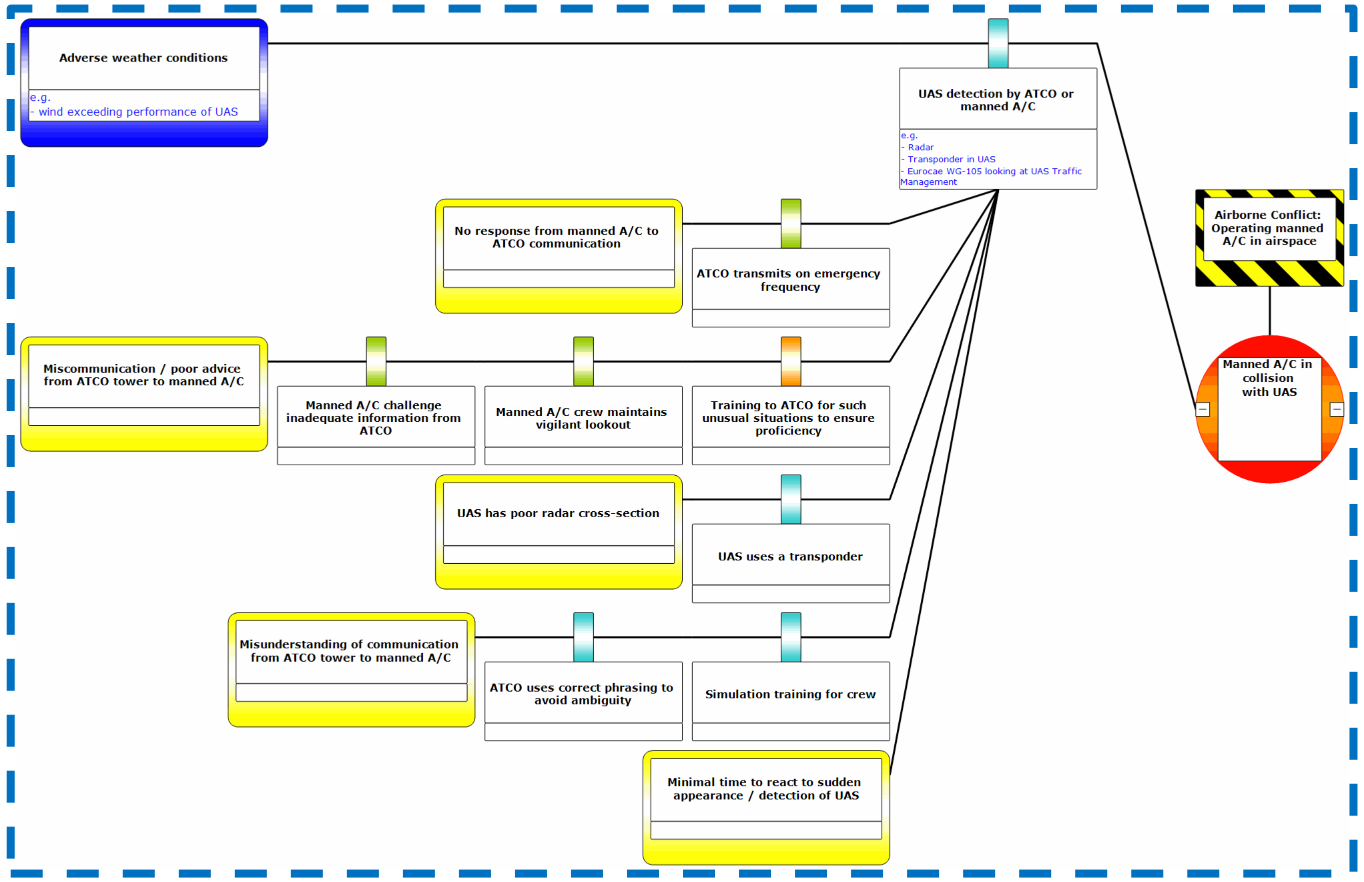




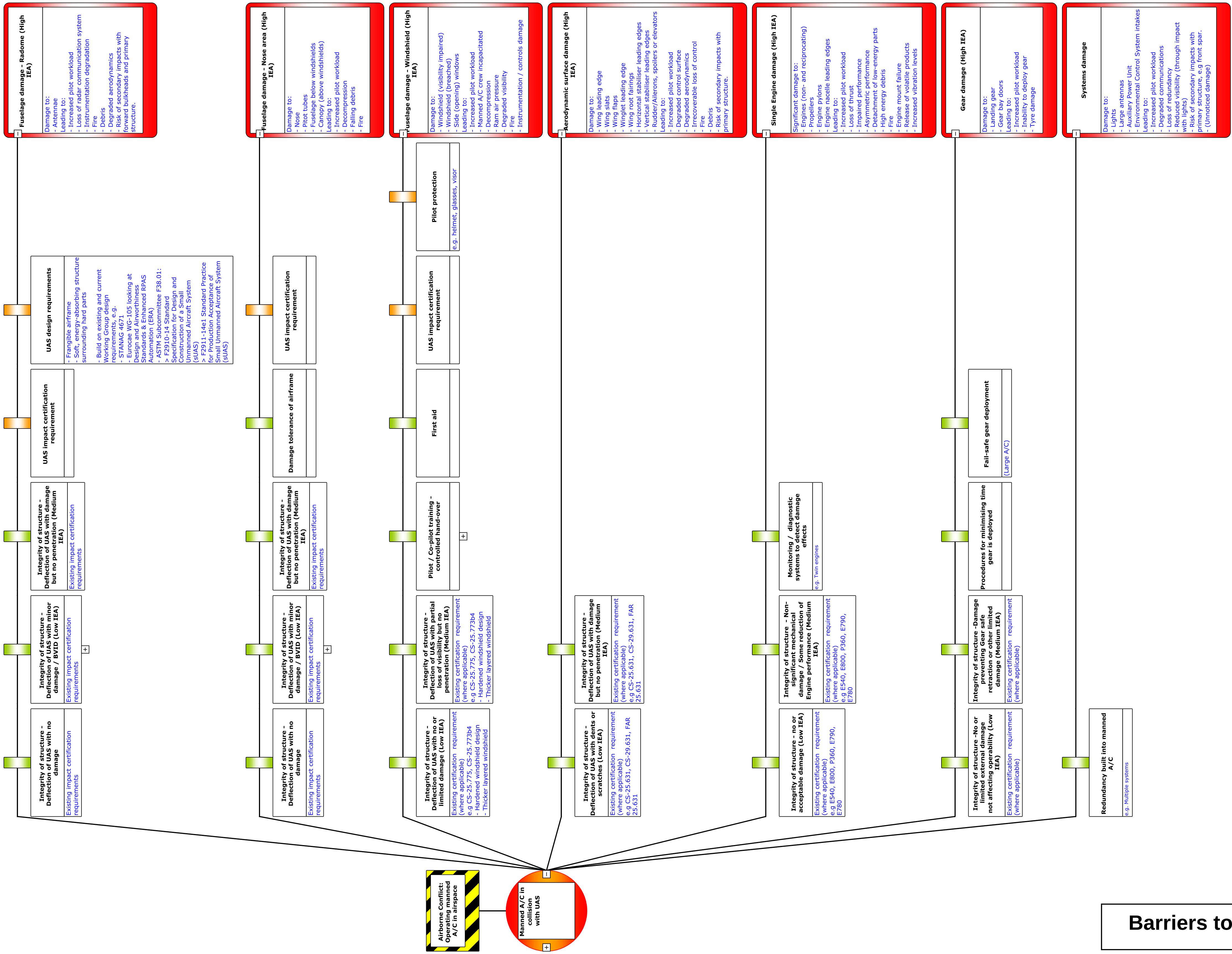


Adverse Weather: Escalations to Barriers

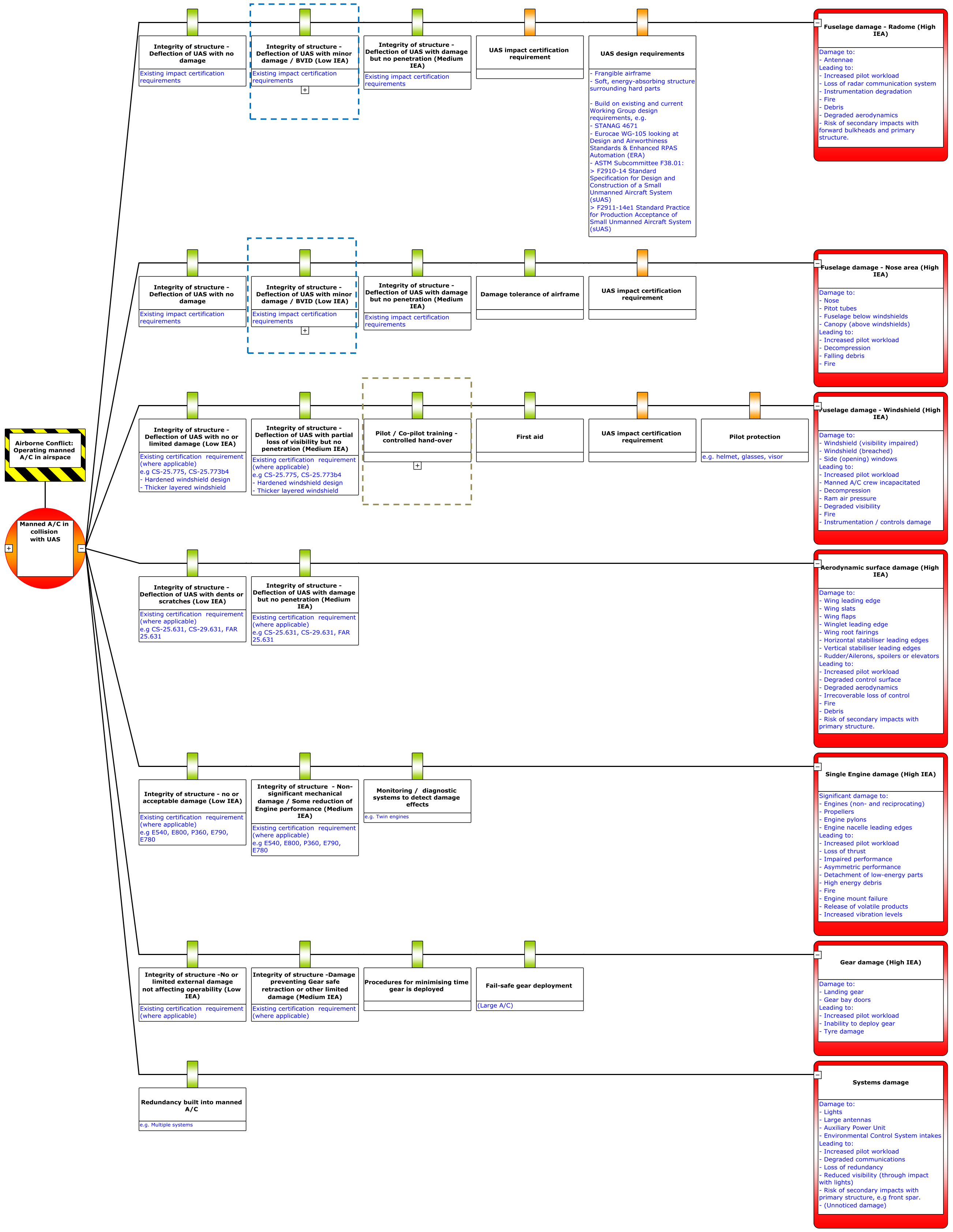


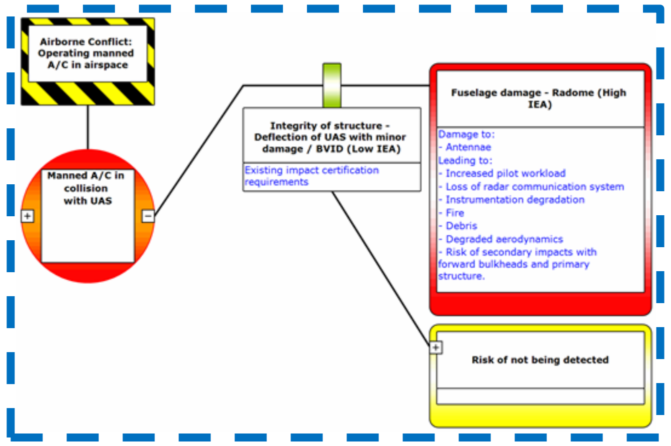


Adverse Weather: Escalations to Barriers

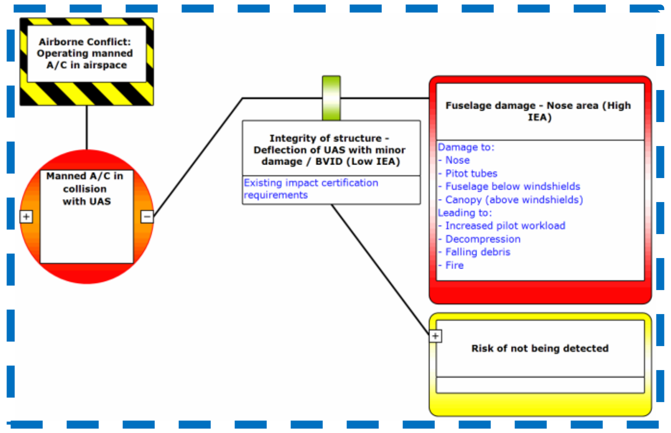


Barriers to Consequences

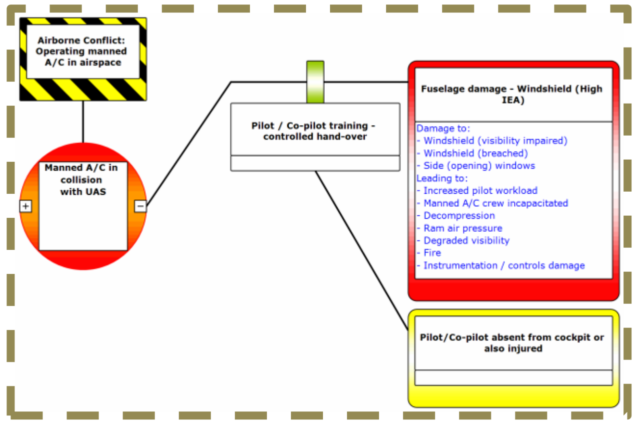




Fuselage damage - Radome: Escalations to Barriers



Fuselage damage - Nose area: Escalations to Barriers



Fuselage damage - Windshield: Escalations to Barriers

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Report Documentation Page

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Abstract This report details the research undertaken by QinetiQ against Work Areas 2 to 5 on EASA's Research Programme on Collisions with Drones (contract EASA.2016.C25). A separate report is also available covering work undertaken on Work Area 1. The objectives of this programme include development of an affordable approach that will enable EASA to assess the risk and severity of impacts between small UAS and manned aircraft. This report includes definition of UAS threats and a means by which to represent them in Finite Element based collision modelling studies, a down-selection of critical aircraft features and the development of an assessment framework that will maximise the benefit of future research against EASA's objectives. A Bow Tie risk assessment is also presented to aid discussions of proportionate and effective preventative and mitigating measures.			
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Last page