Research Programme on Collisions with Drones:
Work Area 1 Final Report

Report

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Work Area 1 Final Report

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Administration Page

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Executive Summary

This report presents the definition of a research programme which, once carried out, will provide stakeholders with validated results in the area of drone-aircraft collision. The approach of the research programme is coherent with the recommendations made by the EASA drone-aircraft collision task force in October 2016. It leverages numerical models and laboratory tests aimed at validating these models, in order to assess the consequence of the impact of several classes of small drones against fixed and rotary wing aircrafts. The research focuses on the assessment of the damage at part level. Once this is known, the consequences at aircraft level can be deduced.

Within the 25 proposed work packages, two are dedicated to the analysis of manned aircraft and UAS operations in order to derive probabilistic indications about, for example, airspace, altitude and speed at which a collision may take place. This, together with the detailed assessment of the physical phenomena of drone collision, would fill current knowledge gaps and provide the possibility to assess potential actions that might be needed to address the drone-aircraft collision risk.

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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 a mid-air collision (MAC) threat between Unmanned Air Systems (UAS) and manned aircraft. The Task Force published its assessment of the threat in October 2016 [1], which included three key recommendations for further research and risk assessment.

1.1.2 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 *(this report)*;
- 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.

1.1.3 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.

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

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

1.2 Scope of this report

1.2.1 The purpose of this report is to draw upon the findings and recommendations from WA2 to WA5, defined in [4], and to outline a programme of work which, if undertaken, will address EASA's requirement to evaluate the MAC threat posed by small UAS to manned aircraft.

1.2.2 This document is the final version of QinetiQ's deliverable report for WA1 and represents Deliverable D5 in QinetiQ's project plan [3].

1.2.3 Following this introduction, Section 2 describes the suggested approach taken to achieving EASA's goals in a pragmatic and cost-effective manner. Section 3, the bulk of this report, describes in detail the proposed research, split out into a series of WPs, with Appendix D summarising each WP in terms of Description; Benefits; Precedents; Dependents; Inputs; Outputs; and Assumptions. Finally, Section 4 describes the suggested phasing of the research work.

2   Approach

2.1   The EASA requirement

2.1.1   The EASA Impact & Hazard Effect Assessment (IHEA) process, shown in Figure 2-1, provides a systematic approach to making aircraft assessments.

2.1.2   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 must be addressed.
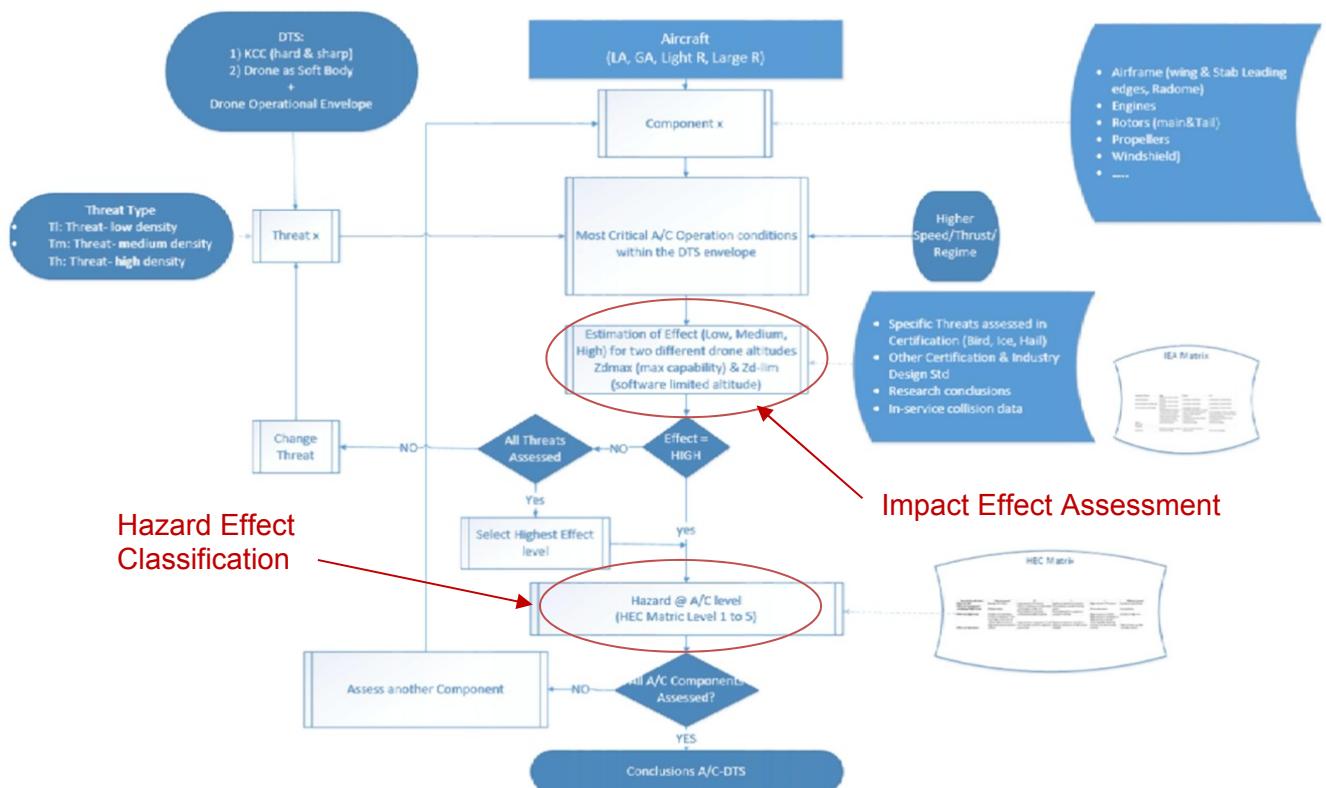

Figure 2-1: EASA Impact & Hazard Effect Assessment process, from [1]

2.1.3   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 where decades of research and testing have led to a greater understanding of the threat zones and a reduced number of variables for test.

2.1.4   A number of approaches could be made to establish solutions to this requirement, some of which are illustrated in Figure 2-2, where the perceived cost against the confidence in the approach is shown. To test a full range of MAC scenarios for all classes of aircraft would be prohibitively expensive, although such an approach would provide a good level of confidence and accuracy in the effect. Whilst the cost of assessing all MAC scenarios using detailed FE modelling would be less, it would still require significant effort to develop appropriately detailed models that are representative of each of the aircraft classes. At the other end of the spectrum, where the cost is low, it might be possible to make scientific estimates of the outcome, but here the confidence in the approach would

be lower, dependent on the considered scenario and current knowledge. A more pragmatic approach, and the one proposed here, is to develop a feature-based approach that is aimed at providing results that can be read-across to a range of different aircraft impact regions, whilst also providing a means by which to undertake more detailed modelling as required. This report expands upon this concept as it represents a cost-effective way to cover the many possible scenarios.
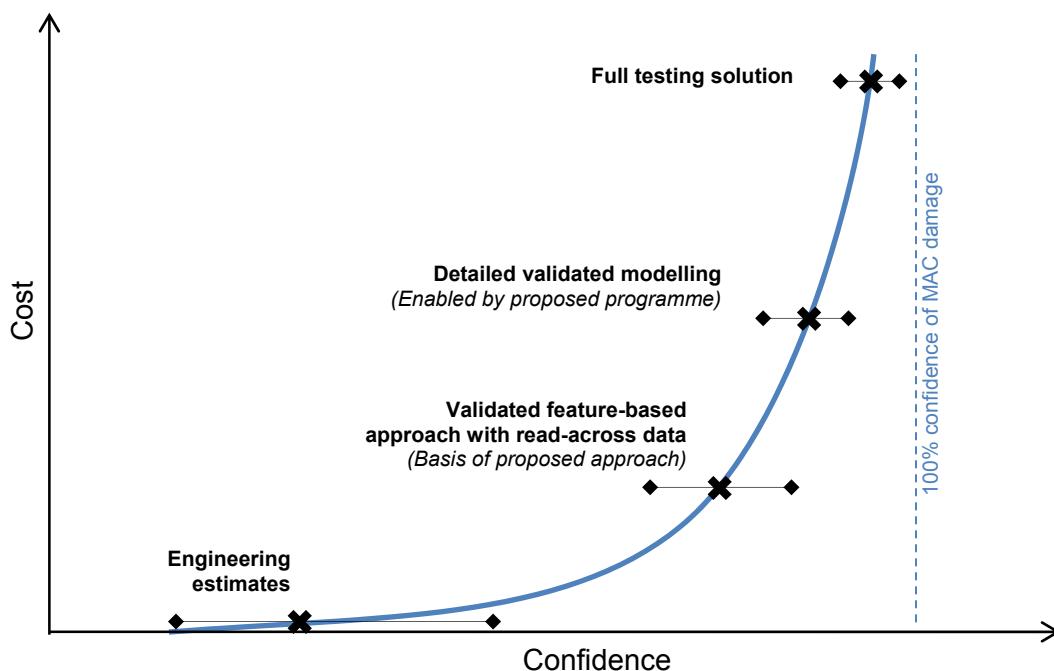

Figure 2-2: Illustration of perceived cost vs confidence for different approaches

2.2 Proposed approach

2.2.1 In recognition of EASA's requirements, the following guiding principles have been 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.
- **Efficient** – 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.

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

2.2.3 In describing this approach, there are extensive references to the development of 'models' and 'modelling'. In the interests of avoiding confusion, a glossary of similar terms relating to modelling activities is included in Appendix A.

2.2.4 A comprehensive description of the proposed approach is covered in Section 3, but a pictorial summary of how the findings and recommendations from Work Areas 2 to 5 influence the proposed programme of work is shown in Appendix B.

2.2.5 A description of how the data generated by the proposed programme of work will be used to make Impact Effect Assessments within the EASA Impact & Hazard Effect Assessment process (Figure 2-1) is included in Section 3 of the Work Area 2 to 5 report [4]. A further example is included in Appendix C.

3 Proposed research

3.1 Introduction

3.1.1 This Section describes a framework of proposed Work Packages to address EASA's requirement for a means by which to assess the effect of collisions between small[1] UAS and manned aircraft.

3.1.2 The proposed Work Packages can broadly be categorised as follows, and as illustrated in Figure 3-1:

- Developing the **UAS Threat Model** (Finite Element (FE) model);
- Assessing the **probability of impact** and associated velocities, and;
- Undertaking **collision assessments** to determine the level of damage that would be sustained to the manned aircraft.

Figure 3-1: Top-level work structure

3.1.3 Although the level of available funding is not currently known, it is understood that it would be desirable to consider a phased approach to future work. In respect to this, alternative approaches are also identified for each Work Package in the event that some research areas are not funded, and Section 4 outlines a proposed phasing for the work.

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[1] Small UAS in this context is defined as UAS up to 25kg in mass (EASA proposed 'Open Category'). However, as discussed in QinetiQ's Work Area 2-5 report [2], the current focus is on quadcopters that are up to 0.25kg ('Harmless'), 0.5kg ('Small'), 1.5kg ('Medium') and 3.5kg ('Large').

3.1.4   As well as allowing activities to be tailored to available funding, a phased approach will also enable the scope of later work packages to be influenced by results from initial activities. This flexibility in scope will ensure that best value is achieved from all research.

3.1.5   The proposed Work Package structure is outlined in greater detail in Sections 3.2 to 3.4 and draft short-form summaries in Appendix D. These include a description of the activity, a summary of the benefits and inputs, outputs and assumptions. Furthermore, Appendix D presents each Work Package in pro-formae giving a brief description of each, along with their benefits, precedents, dependents, inputs, outputs and possible alternatives.

3.1.6   Section 3.2 describes the UAS Threat Modelling Work Packages and Section 3.3 covers activities associated with impact probability. Section 3.4 outlines work associated with collision assessments and includes the greatest number of individual Work Packages; these include activities to assess impacts against a range of prioritised aircraft features using a combination of test, FE model development, validation and analysis.

3.2   UAS Threat Model Work Packages

3.2.1   Two work packages are proposed under the 'UAS Threat Model' title in Figure 3-1. The first Work Package, 'WP-TM1', involves the development of theoretical representations of the UAS configurations whilst 'WP-TM2' compares the impact response of the constituent components to that of conventional Particular Risk threats, such as birds, hailstones, tyre fragments and engine fragments.

3.2.2   Work Package WP-TM1: UAS Threat Model Generation

3.2.2.1   The generation of UAS Threat Models is an essential activity and represents the starting point for any new UAS collision modelling work; Figure 3-2 shows how this WP fits into the top-level work structure.

3.2.2.2   Impact threats of various types are accepted as part of the design and certification requirements for many classes of manned aircraft. Although impacts can be crudely described in terms of the 'projectile' mass, closing velocity and therefore the effective energy, this is not sufficient to characterise the severity of the threat.

3.2.2.3   For example, the level and type of damage that might be expected from an impact with a 4lb bird (which behaves as a fluid upon impact) would be significantly different from that associated with a 3" diameter steel sphere of the same mass. Clearly a UAS does not fit either of these two extremes as it will typically include a combination of hard, soft and frangible components. It is therefore important to determine how each of the primary threat components interact with the aircraft structure and the rate at which their energy is transferred; this characterises the 'signature' of the UAS threats.

3.2.2.4   This Work Package involves the generation of FE representations of each of the UAS threat configurations outlined in Section 2.5 of QinetiQ's report against Work Areas 2 to 5 [4].

3.2.2.5   The process for generating these FE models is also outlined in [4] and involves characterising the impact response of the UAS at component level[2] before assembling

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[2]   Detailed characterisation may be limited to components that are considered to be of greatest threat during an impact e.g. motors and batteries.

the component representations into FE models of complete UAS airframes[3]. The characterisation process should include a combination of physical testing and numerical modelling as identified in Figure 3-2.

3.2.2.6   All testing is to be undertaken at component level (bottom of test pyramid), though for the impact tests, it is important to ensure that a suitable system e.g. an appropriately sized Hopkinson Bar, is used to accurately measure the transient forces. A schematic of the experimental arrangement is shown in Figure 3-3 and example images from similar testing are included in [4].
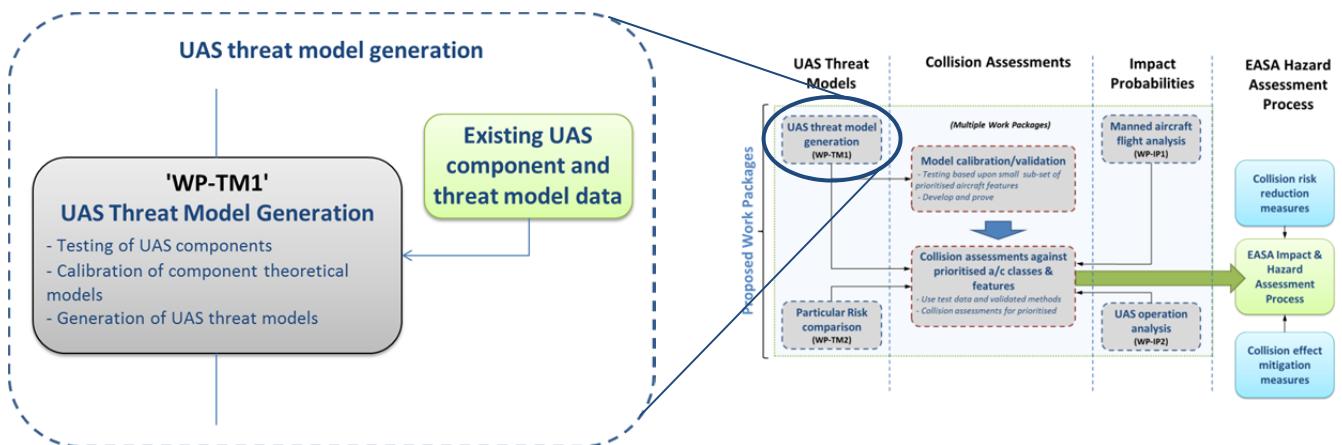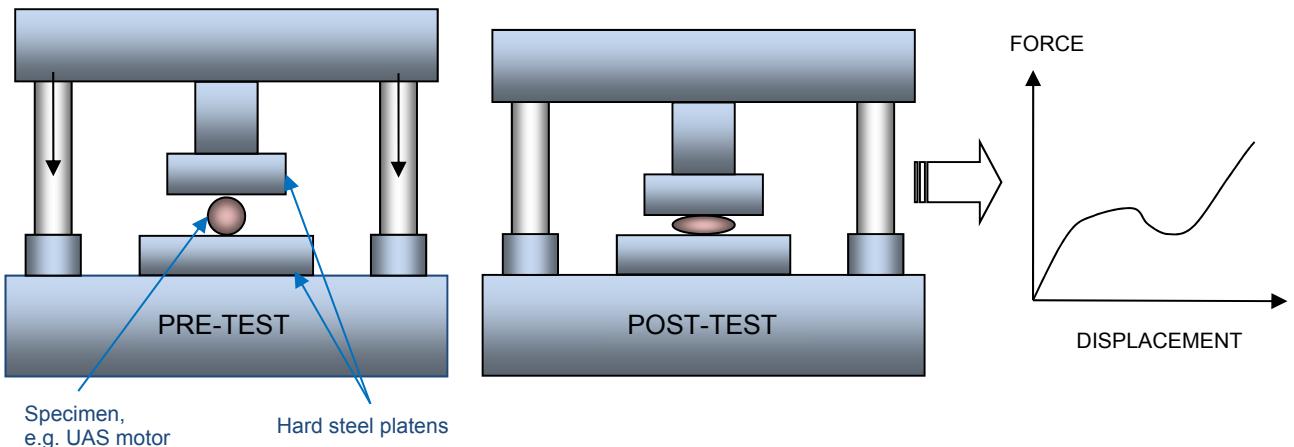

Figure 3-2: UAS Threat Model generation workflow

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[3]   The final Threat Models may exclude some components that are not considered to have a significant contribution on the overall impact threat.

Static crush test machine
Small increments of load or displacement at a slow rate (quasi-static)

Specimen,
e.g. UAS motor

Hard steel platens

Hopkinson bar for measurement of impact response
High speed, high-rate loading due to impacting projectile

Solid end

Specimen, e.g. UAS
motor, launched at
high speed

Gauge

Stress wave

Specimen impacts,
deforms, and rebounds
➔ sends stress wave
along bar,

Figure 3-3: Threat Modelling test schematics

3.2.2.7 Table 3-1 shows an example test matrix for the primary threat components in the four classes of Quadcopter defined in the Work Area 2-5 report [4]. This assumes that each of the down-selected components are tested in just one axis under quasi-static[4] crush conditions and at two different impact velocities.

3.2.2.8 The results from the component testing should be used to develop and calibrate simplified FE representations of each of the main threat components. These individual components should then be assembled into FE models of the different classes of UAS

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[4] In a 'quasi-static' test, the rate of deformation is sufficiently low that inertia effects can be considered to be negligible and no strain rate effects are observed. This would be typical of standard, low rate compression testing.

('Threat Models') so that they can be used in collision assessments, described in later Work Packages. Note that this process of assembling the constituent components (motors, batteries etc) into full UAS Threat Models will also require consideration of the UAS fuselage materials and construction, including joints and appropriate failure mechanisms. An example of a fully assembled UAS Threat Model is shown in Figure 3-4.

3.2.2.9   As identified in Figure 3-2, there is an opportunity within this Work Package to utilise UAS Threat Models that have already been developed within industry for the purpose of collision modelling. However, care must be taken to ensure that any Threat Models that are accepted have been generated and calibrated to an appropriate standard and are applicable to the defined UAS configurations.

3.2.2.10   A short Work Package description for this activity is included in Appendix D.

3.2.2.11   It is also worthy of note that the database of component models and UAS Threat Models generated within the Work Package could be readily expanded to accommodate new UAS configurations and technologies. For minor changes this could be achieved by re-configuring existing components or applying scaling factors. For more significant changes then additional testing and component modelling may be required.

EASA mass class		Component	Number of tests	
			Crush	Impact
'Harmless'	0.25kg	Motor	1	2
		Battery	1	2
		FPV camera	1	2
'Small'	0.5kg	Motor	1	2
		Battery	1	2
		FPV camera (same as 'Harmless')	0	0
'Medium'	1.5kg	Motor	1	2
		Battery	1	2
		Camera	1	2
'Large'	3.5kg	Motor	1	2
		Battery	1	2
		Camera	1	2
		Frame components	1	2

Table 3-1: Example UAS Threat Model generation test matrix

Calibrated motor and internal battery models

Airframe modelled as two shell components, joined together at discrete locations to represent the screws and clips.

Figure 3-4: Example QinetiQ UAS Threat Model

3.2.3 Work Package WP-TM2: Particular Risk Comparison

3.2.3.1 Work Package 'WP-TM2' is an extension of 'WP-TM1' and will allow the UAS impact threat to be quantitatively compared against conventional threats such as hail stones, tyre fragments, birds and engine fragments. This is shown in Figure 3-5.

Figure 3-5: Particular Risk Comparison workflow

3.2.3.2 This activity will include impact testing similar to that described in WP-TM1, whereupon projectiles associated with conventional Particular Risks are fired against an instrumented target. The 'force-time' impact response data generated will be directly comparable with that generated for the UAS components in WP-TM1.

3.2.3.3 The objective of the comparison is to highlight any cases where it can be shown that that the UAS impact threat (for each UAS mass class) is less severe than conventional

Particular Risks[5]. Where such an argument can be made, it will provide early evidence for EASA's hazard assessments without the need for additional testing or analysis.

3.2.3.4 In order to benefit from economies of scale, it is proposed that this activity should be conducted at the same time as 'WP-TM1' and include impact tests against the same configuration of instrumented targets. There may be opportunities to utilise existing test data for some impact cases though it would be beneficial to complete the relatively small number of additional tests using the same experimental arrangement.

3.3 Impact probabilities

3.3.1 The safety case associated with the concurrent operation of small UAS and manned aircraft must consider both the likely severity of a collision and also the probability of occurrence.

3.3.2 Existing Particular Risk certification requirements make the assumption that the aircraft (or at least, the aircraft type) will experience the relevant impact threat during its design life. However, there is no equivalent certification requirement for UAS collisions and although incidents involving UAS have been well publicised, their frequency in recent years is orders of magnitude lower than other threats such as bird strikes[6].

3.3.3 Two Work Packages are therefore proposed to firstly examine how different classes of manned aircraft are operated (WP-IP1) and secondly how UAS are operated, including consideration of future trends (WP-IP2).

3.3.4 Work Package WP-IP1: Manned Aircraft Flight Analysis

3.3.4.1 The purpose of this Work Package is to gain a probabilistic understanding of operating behaviours of manned aircraft. This will be used to determine the likely effectiveness of potential measures to limit the locations and altitudes at which UAS can operate as a means to increase aviation safety. It will also provide statistical data to determine the likely (rather than maximum) speeds at which collisions may occur for various classes of manned aircraft.

3.3.4.2 Large datasets of historic flight information exist and can be interrogated to provide statistically meaningful assessments of the usage patterns of different classes of manned aircraft. It is proposed that this activity should include the following:

- Statistical distribution of flight speeds with respect to height above ground (by aircraft class)

  – To determine probable collision speeds as a function of UAS altitude capability/restrictions.

- Occurrences and durations of flight activities within discrete lower altitude bands (by aircraft class)

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[5] Whilst a very crude comparison between UAS threats and conventional Particular Risks could be made based upon their relative kinetic energies, this is not sufficient to define the severity of the impact.

[6] In the UK during 2016 over 1,800 bird strikes [7] were confirmed by the Civil Aviation Authority (CAA) plus an additional 821 unconfirmed impacts and 268 near misses. In the same year, up until the end of May, approximately 250 remotely piloted air systems (RPAS) related 'occurrences' (including near misses) were catalogued by EASA across the whole of Europe [1].

> – To estimate relative probability of collision as a function of UAS altitude capability/restrictions.

- Occurrences and durations of flight activities within discrete lower altitude bands, excluding regions around airports or for take-off and landing (by aircraft class)

> – To assess the potential effectiveness of restricting UAS operations in the vicinity of airports or specific high traffic areas.

3.3.4.3　The output of this Work Package will be aimed at understanding the probabilities and impact speeds of collisions with UAS, but it would also be highly applicable when considering other aviation hazards such as bird strike.

3.3.4.4　If this activity is not funded during initial phases of a UAS collision assessment programme then it would be necessary to estimate aircraft speeds at credible altitudes; this may include consultation with pilots, reference to performance specifications for General Aviation classes and/or input from organisations such as Eurocontrol.

3.3.5　Work Package WP-IP2: UAS Operation Analysis

3.3.5.1　This second Work Package is analogous to WP-IP1, but is intended to assess operational behaviours of UAS rather than manned aircraft. The combined outputs from the two Work Packages would provide data to allow the probability and speed of collisions to be assessed, thereby enabling informed decisions to be made using principles of risk management rather than simply evaluating worst-case scenarios.

3.3.5.2　The level and type of data that is available to support this activity is likely to be different to that for manned aircraft. Possible sources may include:

- Performance limitations[7], practical usage limitations[8] and software-based restrictions[9] imposed on UAS
- Analysis of reported incidents
- Survey of UAS ownership and usage
- Flight plans and licenses for commercial operators
- Data collected through voluntary apps such as the UK National Air Traffic Control Services (NATS) 'Drone Assist' [5]

3.3.5.3　The usage of UAS is evolving rapidly and is fuelled by technological advances, reduced cost of ownership, consumer trends and commercial opportunities for small businesses (e.g. aerial photography) and large corporations (e.g. delivery services). There are also greater levels of resources being put into publicising the potential hazards associated with UAS operations, providing guidance on safe usage and legislative measures. Each

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[7]　Performance limitations include physical limits on flight operations at altitude.

[8]　Practical usage limitations might include consideration of whether it would be practical to operate the UAS at high altitude and also whether battery limitations would also place usability limits, rather than just physical capability limits. This is particularly relevant for 'Harmless' and 'Small' UAS, which are more suited to remotely piloted (rather than pre-programmed), low-level operation.

[9]　Limitations on attained altitude imposed through Firmware. Note that there are currently cases of such limitations being imposed by manufacturers and then nullified by non-official third-party software; however, it is likely that users who actively seek to circumvent these features would represent a small minority.

of these factors influence the way in which UAS are operated and the scale of their usage.

3.3.5.4   It may be sufficient to make basic assumptions about UAS usage during early phases of a UAS collision assessment programme. However, as usage patterns become increasingly complex, flight endurance times and payloads increase, and governing bodies face increasing challenges to implement effective but proportionate legislative measures, the benefits of a thorough understanding of UAS usage increases.

3.4   Collision assessments

3.4.1   General approach to collision assessment

3.4.1.1   Although it might be the most definitive and comprehensive approach, full-scale impact testing of all manned aircraft designs/classes against each UAS threat is not a practical option and would be prohibitively expensive. For this reason it is necessary to consider prioritised critical areas using a combination of feature-based tests and analysis. The recommendations from Work Area 3, described in [4], are assimilated into this proposal of work.

3.4.1.2   The physical impact tests should be against examples of the prioritised critical areas/features identified in Figure 3-6, which also shows the associated Work Package label. These tests will provide data that can be used to develop and validate models, and allow read-across to different aircraft structures. The Work Packages for the collision assessments are therefore arranged by feature type, typically with individual activities defined for the manufacture, test & validation, and broader assessment phases.

3.4.1.3   The nomenclature for the collision assessment Work Package labels includes single-letter codes for the feature type and configuration. For example, 'WP-CA-P-M1' is 'Work Package (WP) – Collision Assessment (CA) – Panels (P) – Metallic (M) - <WP number>'. The letter codes are highlighted in Figure 3-6.

3.4.1.4   The proposed phasing is discussed further in Section 4, which is based upon perceived priority and knowledge of existing data that may be relevant to specific areas. However, because it is not yet defined who may conduct any future programmes, and therefore what existing data they may have access to, the full suite of Work Packages are described herein for completeness.

3.4.1.5   The following Sections outline the proposed activities against each of the prioritised features shown in Figure 3-6. The first of these covers impacts against 'Panels', which are further sub-divided by material type/structural configuration in order to be representative of a large number of general aircraft impact zones. Later Sections cover Windshields, Engines and Rotors.

Figure 3-6: Prioritised a/c features for collision assessment

3.4.2 Panel collisions

3.4.2.1 Introduction to Panel collisions

3.4.2.1.1 The Panels Work Packages are sub-divided by material type/structural configuration as shown in Figure 3-6. This demarcation is considered necessary because each of these configurations will behave differently and exhibit different failure modes; they must therefore be tested and the FE models validated separately.

3.4.2.1.2 However, notwithstanding the importance of recognising their uniqueness, the workflow for each configuration is similar. Therefore, the following Sections describe the Work Package structure for all of the Panel configurations. These are split as follows:

- Design and manufacture (Section 3.4.2.2)
- Testing and model calibration (Section 3.4.2.3)
- Feature assessments (Section 3.4.2.4)

3.4.2.1.3 In order to maintain affordability, the number of panels of each type proposed within this programme represents the minimum that are required for basic validation of good quality FE modelling methods. The number of test specimens could be increased to provide a greater dataset for model development and validation, though this will increase the cost of manufacture, test and validation exercises. Particular consideration may be given to inclusion of additional composite panels as these are likely to present the greatest challenges when developing accurate FE impact models with appropriate failure modes. Additional composite panels could include different materials, lay-ups, features or testing with a greater range of impactors.

3.4.2.2 Work Package WP-CA-P-M/C/S1: Panels - Design and manufacture of test panels & fixture

3.4.2.2.1 This section is relevant to metallic (M), monolithic composite (C) and sandwich composite (S) panels. The workflow for WP-CA-P-M/C/S<1-3> is shown in Figure 3-7.

3.4.2.2.2 The design and manufacture of a panel, for the purposes of the programme will allow control over the simplicity of the design and the materials making up the feature will be known. This is important as the panel impact tests will be used to validate FE models of the impact collision and so reduces the number of unknowns.

3.4.2.2.3 For initial planning purposes, it is proposed that the panel be curved in a Leading Edge type design[10]. The shape, thickness and materials/lay-up of this specimen will be designed such that it is representative of a critical feature on an aircraft class of primary interest e.g. passenger aircraft such as CS-25, CS-23 or CS-29.

3.4.2.2.4 As a minimum only one panel type is required, as this is for the purposes of FE model validation of the impact collision. For a given projectile type, a number of panels (typically a minimum of three) will be required to estimate not only the penetration threshold velocity, but the levels of any damage at velocities below this threshold; this information will be used to calibrate material models to predict similar outcomes, giving confidence in the further use of the FEM.

3.4.2.2.5 An alternative to this design and manufacture activity would be to source multiple examples of relevant aircraft components/sub-assemblies for test. Whilst this may avoid the need to manufacture any new specimens and would provide excellent test results for a given impact scenario, it is envisaged that these advantages would be outweighed by the following factors:

- Difficulties sourcing appropriate aircraft structures in the required quantities;
- Requirement to mount complex aircraft sub-assemblies in test fixture whilst ensuring well-defined support/boundary conditions[11];

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[10]   Other panel configurations could be considered. Ideally the selected configuration would be broadly representative of one of the down-selected critical aircraft features and also be relatively inexpensive to manufacture.

[11]   Well-defined support/boundary conditions are required for all tests and FE models, but complex configurations will require bespoke, more costly, support structures and may be subject to greater uncertainty.

- Increased structural complexity may not lend itself to efficient model validation and read-across of results, and;
- Detailed structural survey would be required to ensure that modelling work accurately represents the test specimen.
- Potential commercial difficulties obtaining, sharing and publishing detailed design data and materials data from aircraft OEMs.

3.4.2.2.6   It should be noted that this set of Work Packages and the ones defined in Section 3.4.2.3 (i.e. WP-CA-P-M<1-2>, WP-CA-P-C<1-2>, WP-CA-P-S<1-2>) would not be required if it is decided that, for the purposes of initial work, existing FE models of UAS and a/c panel features are sufficiently mature to be applied without further validation. However, this is a questionable alternative approach as this is not yet a well understood threat and EASA requires evidence of the validity and accuracy of numerical models.
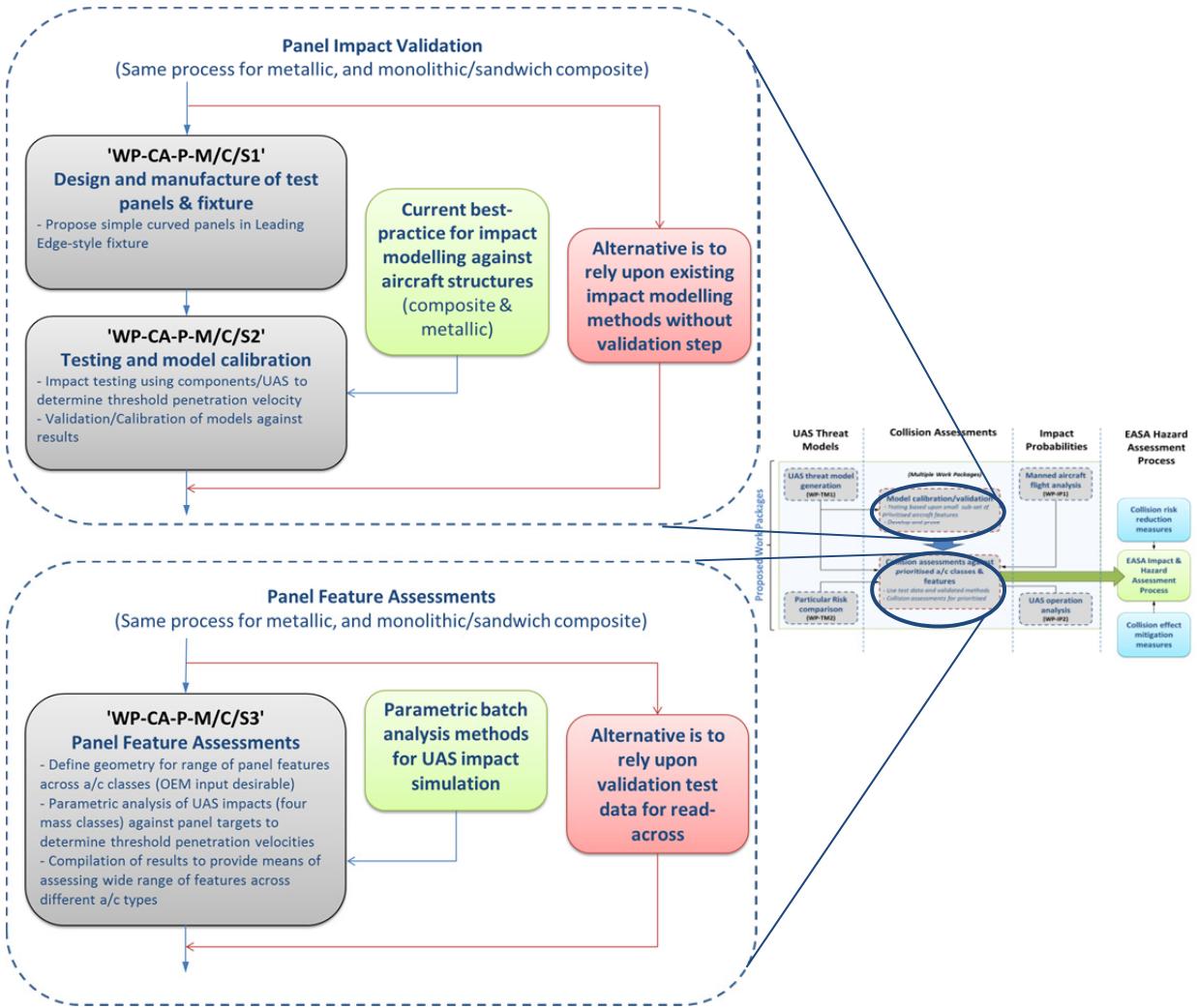

Figure 3-7: Panel feature assessment workflow

3.4.2.3 Work Package WP-CA-P-M/C/S2: Panels - Testing and model calibration

3.4.2.3.1 The purpose of these Work Packages is to create and validate FE models of impacts against simple panel features; this will give confidence in use of the FE models for subsequent prediction of the threshold penetration velocity against a/c features (WP-CA-P-M/C/S3).

3.4.2.3.2 The Work Package will involve a series of physical impact tests, using UAS components and/or whole UAS assemblies, against the manufactured panels (WP-CA-P-M/C/S1). The outcome will provide validation "points" for representative panel configurations, which can be used to develop and validate FE models, giving confidence in their exploitation in subsequent WPs.

3.4.2.3.3 All physical tests should be recorded using high speed video systems and visible damage should be captured in post-test photographs. For composite panels (monolithic or sandwich panels), appropriate non-destructive evaluation (NDE) should be undertaken before and after impact to determine the extent of damage. This is particularly important for cases where there are no obvious visible signs of damage, but where barely visible impact damage (BVID) could be present.

3.4.2.3.4 The FE modelling activity will use current best-practice for impact modelling against aircraft structures (composite & metallic). The physical testing will run in parallel with the theoretical activities which will allow validation/calibration of FE models against the physical results; the modelling can be used to feedback into the physical testing in terms of required test impact velocity. The outcome will provide validated FE models which can be used with confidence[12] in further, more complex, collision modelling activities.

3.4.2.4 Work Package WP-CA-P-M/C/S3: Panels - Panel Feature Assessments

3.4.2.4.1 These Work Packages (i.e. WP-CA-P-M3, WP-CA-P-C3, WP-CA-P-S3, all of which are covered by this description) utilise the validated FE models and limited panel test data from 'WP-CA-P-M/C/S2' to efficiently assess multiple collision scenarios for different classes of UAS and manned aircraft.

3.4.2.4.2 With the input of aircraft OEMs or structural surveys of example aircraft, the geometries for a range of common/generic panel features across aircraft classes will be defined for analysis. Model generation and parametric analysis of UAS impacts (four mass classes) should be carried out against the panel targets to determine levels of damage and threshold penetration velocities.

3.4.2.4.3 Data from testing in WP-TM1 (UAS components) and WP-TM2 (Particular Risks) can be used to reduce the scope of the mid-air collision scenarios where the UAS threat can be enveloped into current certification of the Particular Risks. Furthermore the data from the output of the impact probabilities WPs (WP-IP<1-2>) that will allow the speed of collisions to be assessed, can be used to limit the number of scenario that need to be modelled.

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[12] The level of confidence in each model will depend upon the extent to which it differs from the configurations against which it was validated. For certification purposes it is not normally permissible to use modelling evidence to extrapolate beyond validation configurations. However, for the reasons outlined in Section 2, a more pragmatic approach is necessary within this initial programme of proposed work.

3.4.2.4.4   The results of the WP will provide a means of assessing a wide range of features across different a/c types and feed information into the EASA Impact Effect Assessment (IEA) at a/c component level to classify the effect (i.e. High, Medium, Low).

3.4.2.4.5   As shown in Figure 3-7, there are opportunities to exploit existing tools and capabilities to aid this activity, which is likely to be computationally intensive and require large amounts of data to be processed in a consistent manner. For example, tools and methods which allow parametric UAS collision FE models to be set up, run and post-processed in parallel batches, in order to significantly improve efficiency and quality.

3.4.3   Windshield collisions

3.4.3.1   Introduction to windshield collisions

3.4.3.1.1   Windshields have been down-selected as critical features across all aircraft types as they are exposed, susceptible to damage/failure and are critical to the safe operation of the aircraft.

3.4.3.1.2   The windshield Work Packages, described below, include the following activities:

- Constitutive materials (Section 3.4.3.2)
- Windshield model validation (Section 3.4.3.3)
- Windshield impact assessment (Section 3.4.3.3.7)

3.4.3.1.3   Note that these follow a different format to the Panels Work Packages because of the challenges associated with their assessment. For example, because of the complex interplay between the relatively brittle transparencies and their support structure, it is highly preferable to test genuine aircraft windshields, installed within fuselage structures rather than manufacture surrogate specimens. Furthermore, the brittle materials used in monolithic and laminated transparencies are known to be difficult to accurately predict the failure of, so a greater emphasis is required on model development and validation. However, these difficulties may be significantly offset by prior experience in previous studies [8].

3.4.3.2   Work Package WP-CA-W1: Windshields - Constitutive materials

3.4.3.2.1   The workflow for WP-CA-W<1-3> is shown in Figure 3-8.

3.4.3.2.2   It is known that accurate modelling of the failure response of glass is not a trivial task; the material model e.g. elastic-plastic/brittle/etc. and its parameters, along with the elements and mesh density for FE approaches all require detailed consideration. Basic material properties such as elastic moduli, density and Poisson's ratio will need to be sourced but the most appropriate damage initiation and failure terms will need to be determined.

3.4.3.2.3   The aim of this WP will be to research and collate appropriate materials property data for aerospace windshields and undertake static and/or impact testing against coupon/plate specimens to improve confidence in their failure response. This will greatly de-risk subsequent test and modelling activities.
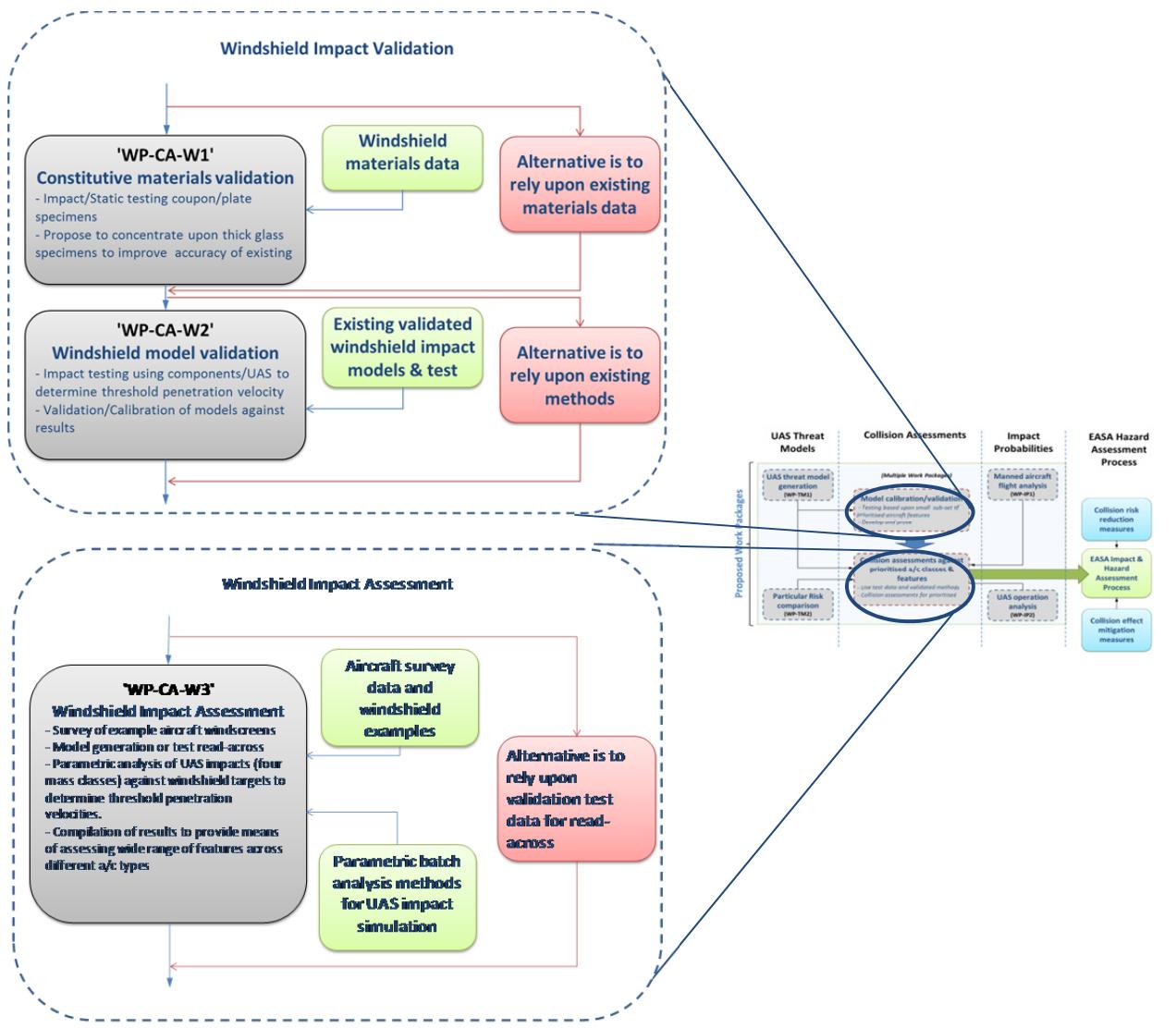
Figure 3-8: Windshield feature assessment workflow

3.4.3.3 Work Package WP-CA-W2: Windshields - Windshield model validation

3.4.3.3.1 The purpose of this Work Package is to create and validate the FE models of the windshields; this will give confidence in use of the models for subsequent prediction of the threshold penetration velocities against other aircraft windshields (WP-CA-W3).

3.4.3.3.2 Physical impact testing is proposed to be carried out using whole UAS assemblies against windshields installed in sections of fuselage. The aim of this is to determine levels of damage and threshold penetration velocity. The outcome will provide validation "points" for different classes of windshield and data that will be immediately exploitable for IEAs.

3.4.3.3.3 It remains to be defined who will source the appropriate test hardware, including all windshields and sections of fuselage, along with construction details of the windshields. However, it is assumed that detailed CAD models of the windshields and fuselage structure will not be available, so this will be obtained via a survey as part of the Work

Package activities; this will enable the generation of accurate FE models of the windshields, window frames and immediate aircraft fuselage structure.

3.4.3.3.4 The modelling activity would be carried out in parallel with the physical testing and initial results from impact predictions will be used to determine impact speeds for the first tests. The test speeds will then be iterated – using the available windshield specimens – to determine the impact threshold velocity (velocity at which the projectile is expected to penetrate the structure) and observe the level of damage at lower velocities.

3.4.3.3.5 The threshold velocity results provide significantly more information than one-off, single-velocity impacts and are highly beneficial when developing and validating FE modelling methods. The outcome of the exercise will be validated FE models which can be used with confidence in further, more complex, modelling activities involving different classes of UAS and designs of windshield.

3.4.3.3.6 It is proposed that three windshield configurations are tested, including different combinations of materials and thicknesses; this should include an example of a CS-25 windshield plus two others from CS-23, CS-27 and CS-29 classes. Up to five sets of impact test are proposed, using a combination of different UAS projectiles. The test matrix should be determined as part of the Work Package and aim to provide a robust set of test evidence as well as data for model validation.

3.4.3.3.7 As indicated in Figure 3-8, there are opportunities to exploit existing research and data to greatly reduce the scale of this activity. If previous research, associated data and validated modelling methods were available to EASA then future activities could be directed towards incremental improvements to better represent windshield configurations in civil aircraft.

3.4.3.4 Work Package WP-CA-W3: Windshields - Windshield impact assessment

3.4.3.4.1 This Work Package will provide an efficient method of determining the level of damage and threshold velocities of different mid-air collision scenarios for different classes of UAS against relevant aircraft windshields. This Work Package is primarily a FE modelling activity.

3.4.3.4.2 With input from airframe OEMs or major suppliers, the initial work will involve a survey of example aircraft windscreens and fuselage structures for CS-classes of interest.

3.4.3.4.3 FE model generation and parametric analysis of UAS impacts (four mass classes) will be carried out against the windshields to determine damage levels and threshold penetration velocities.

3.4.3.4.4 The results of the WP will provide a means of assessing a range of windshield classes against mid-air collisions with a UAS, and feed information into the EASA Impact Effect Assessment to classify the effect (i.e. High, Medium, Low).

3.4.3.4.5 As noted earlier, relevant data exists for impacts against various classes of aircraft windshields so there are opportunities to read-across some of these results and methods.

3.4.4 Engine ingestion

3.4.4.1 Engine ingestion introduction

3.4.4.1.1 Ingestion of a small UAS into an engine has the potential to cause significant damage and complete loss of thrust.

3.4.4.1.2 The effective impact energy associated with engine ingestion is significantly greater than collisions with the airframe because of the high rotational speed of the fan. Whilst fan blades are designed to withstand ingestion of birds, hail, ice and small foreign objects such as runway debris, their survival and continued operation after a UAS impact remains uncertain.

3.4.4.1.3 Work undertaken by a team at Virginia Polytechnic in the United States of America simulated ingestion of an 8lb (3.6kg) quadcopter into a 9-foot (2.75m) diameter turbofan engine at take-off conditions [6]. Although it is not known how accurately the UAS was modelled, the predicted result was failure of multiple fan blades and catastrophic failure of the engine.

3.4.4.1.4 It is assumed that full-scale testing of high speed UAS ingestion into a running engine would be prohibitively expensive. However, a combination of modelling methods and testing against fan blades would provide an initial indication of the likely damage that would be caused in the event of a collision. The following Work Packages are outlined to tailor Threat Models so that they are more-applicable to blade impacts and develop and validate modelling methods that will enable ingestion assessments to be made for various classes of engine and UAS.

- Engine impact Threat Model enhancement (Section 3.4.4.2)
- Engine blade model development (Section 3.4.4.3)
- Engine ingestion modelling (Section 3.4.4.4)

3.4.4.1.5 In formulating these Work Packages for engine ingestion (fan blade impact), it is assumed that engine fan blades can be sourced for the purpose of test, and that sufficient structural design information can be made available to develop impact models. These are significant assumptions and there is a risk that difficulties will be encountered gaining access to suitable specimens and basic design information[13].

3.4.4.1.6 If test specimens and/or design data is not available then the approach to assessing engine vulnerabilities may need to be revisited. Alternative approaches might include engagement with American programmes or acquiring data via structural surveys of example components.

3.4.4.1.7 It should be noted that these work packages only consider impacts against fan blades and ingestion into the bypass flow. This is considered to be the most appropriate starting

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[13] It is proposed that these initial impact test/assessment activities should focus upon traditional, hollow titanium blades rather than new composite designs. This focus will ensure that the results are applicable to in-service turbofan configurations and also reduce the risk of unavailability of hardware and basic design details.

A similar process may be adopted for composite designs, but this would require greater effort, increased testing and greater access to design data. Due to the commercial sensitivities of new composite blade designs, it is considered to be unlikely that this level of data would be readily available.

point but if it is shown that fan blades are tolerant of UAS impacts, then additional work may be required to assess other, more complex ingestion scenarios. For example, extended studies could determine the effect of ingestion into the core and/or more detailed assessment of the dynamic response of the engine to impact events.

3.4.4.2 Work Package WP-CA-E1: Engines - Engine impact Threat Model enhancement

3.4.4.2.1 The workflow for WP-CA-E<1-2> is shown in Figure 3-9.

3.4.4.2.2 This WP is similar to WP-TM1 but involves testing UAS components against a secondary 'chopping' impact mode, such as might be experienced during in impact with a fan blade. The work will be carried out for the components of different classes of UAS, i.e. Harmless (0.25kg), Small (0.5kg), Medium (1.5kg) and Large (3.5kg). The output will complement the existing database of component theoretical models from WP-TM1, which would already have data to simulate a full frontal impact on the blade face by the hard parts of the UAV (i.e. motors and battery and other metallic structure) and also ejection of components/debris from the trailing edge of the blade.

3.4.4.2.3 Data from the testing will be used to calibrate component theoretical models by refining the material response and failure laws for each component.

3.4.4.2.4 An alternative to this Work Package would be to use the models developed within 'WP-TM1', though this may not give the correct response when subjected to a high speed cutting action rather than the blunt impact used to define their formulation.
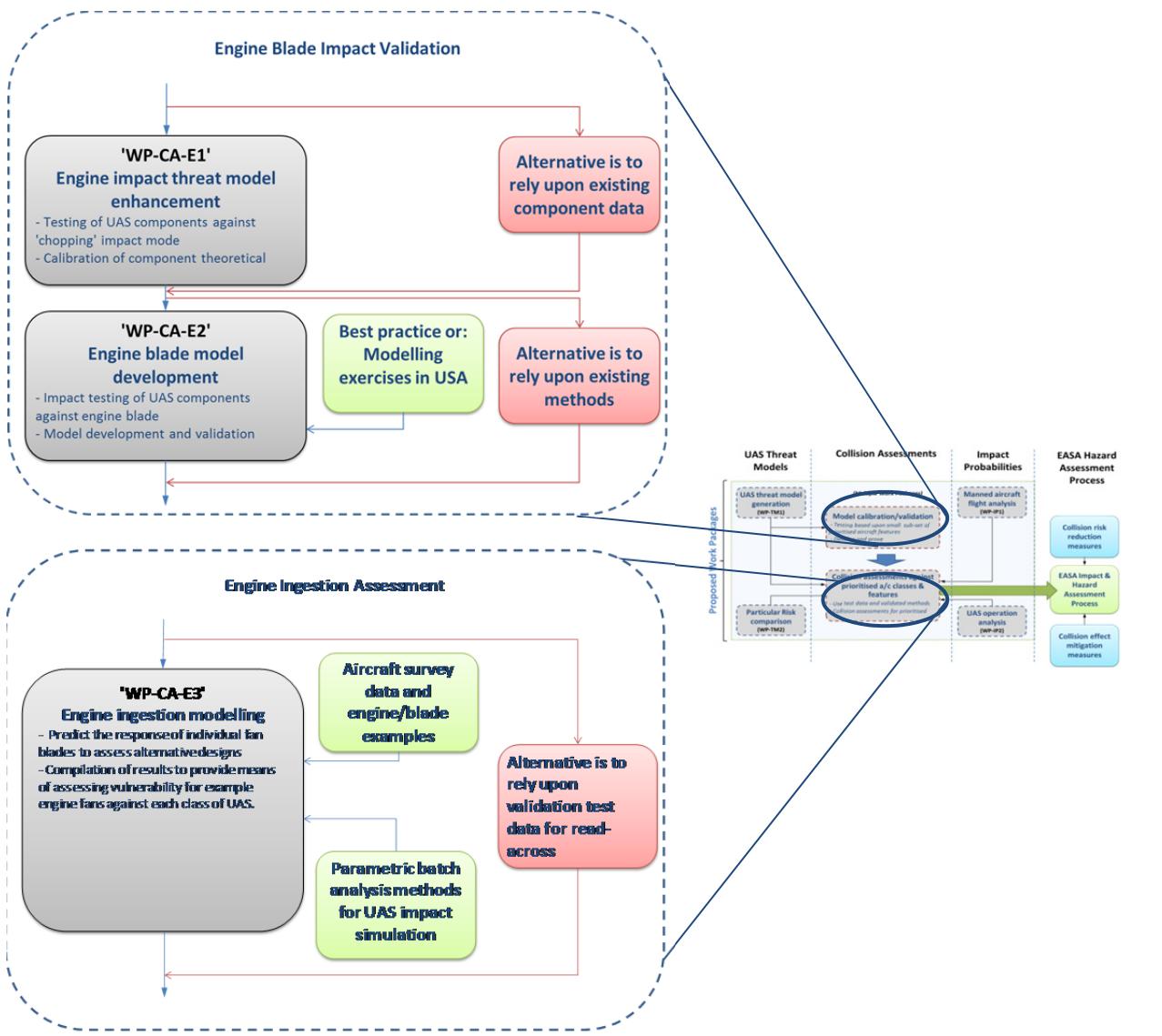
Figure 3-9: Engine blade feature assessment workflow

3.4.4.3 Work Package WP-CA-E2: Engines - Engine blade model development

3.4.4.3.1 The purpose of this Work Package is to develop an understanding of the effects that ingestion of a UAS will have on the main fan stage of an example turbofan engine. It includes impact testing of UAS components against fan blades, which will be used to develop and validate an FE model. This model will then be used to predict the level of damage expected in the event of a whole UAS impacting against the rotating fan blades.

3.4.4.3.2 Engagement with the engine OEM would be required in order to efficiently establish details of the materials used and provide CAD models of the components. If this is not possible then it would be necessary to obtain data from geometric surveys, and either materials testing or assumptions based upon published data.

3.4.4.3.3 Physical impact tests will be carried out using down-selected UAS components against blades to determine likely damage levels. In these tests the blades will be held stationary (no rotational or thrust loads) and the components will be fired at an angle to account for their relative forward and rotational velocities.

3.4.4.3.4 As well as recording the impacts with high-speed video and evaluating the level of damage sustained post-test, instrumentation should also be included to record deflections of the blade as this will provide useful evidence for comparison with FE modelling results.

3.4.4.3.5 The aligned FE modelling activity will develop upon current best-practices to predict the level of damage caused to the fan blades. The experimental results will allow development of the modelling methods, which can then be used to assess a wider range of ingestion scenarios.

3.4.4.3.6 After the initial model development activity (and comparison with test results) has been completed, the analysis will be extended to account for the rotational forces on the fan blades and ingestion of whole UAS, rather than just components. This will be closer in scope to the simulations run by Virginia Polytechnic [6], though the planned activity focusses on the fan stage so the model details will be tailored to this requirement.

3.4.4.4 Work Package WP-CA-E3: Engines - Engine ingestion modelling

3.4.4.4.1 This Work Package builds upon WP-CA-E2 but expands the scope to include an additional fan design e.g. for smaller/larger engine.

3.4.4.4.2 The activity doesn't include any additional testing but exploits the modelling methods developed in WP-CA-E2 to predict the response of the additional fan design to ingestion of each of the four different classes of UAS.

3.4.4.4.3 Engagement with the engine OEM(s) would be required in order to efficiently obtain sufficient details to make accurate assessments of UAS impacts. If this is not possible then it would be necessary to base work on surveys and researched materials data.

3.4.5 Rotor impacts

3.4.5.1 Rotor impacts introduction

3.4.5.1.1 For the purpose of this study, 'Rotor impacts' includes main and tail rotors, rotor hubs and could also be extended to include propellers from fixed wing aircraft.

3.4.5.1.2 Relative to main rotors, tail rotors are of lighter construction with less substantial leading edges; they are therefore judged to be more susceptible to damage in the event of an impact. The probability of bird strikes against tail rotors may be reduced due to them being shielded by the main rotors and fuselage during forward flight (and birds are unlikely to fly into them side-on). However, stray UAS would not necessarily have the same situational awareness, nor a sense of self-preservation, so on this basis side-on impacts with tail rotors are more plausible.

3.4.5.1.3 Like fan blades, the high rotation speed of tail rotors mean that effective impact energies are high regardless of the flight speed of the rotorcraft or UAS. For these reasons, and their criticality to safe operation, impacts against tail rotors are considered to be a priority.

3.4.5.1.4   Impacts against rotor hubs are also of concern due to their criticality and possible vulnerability to damage. The hub includes items such as the rotating swash plate, pitch and teeter hinges, and the more delicate linkages to control the blade pitch. It is deemed important to investigate the effect that a collision with a UAS might have on this control area.

3.4.5.1.5   Although not included in the current list of Work Packages, propellers could also be assessed using a similar approach to that used for the Tail Rotors i.e. limited testing against components with aligned FE model validation, followed by additional modelling activities to assess the response of impacts against whole UAS and accounting for rotational effects (and possibly propeller thrust and drag) for one or more propeller configurations.

3.4.5.1.6   The following Work Packages are planned:

- Tail rotor impact model validation (Section 3.4.5.2)
- Tail rotor impact assessments (Section 3.4.5.3)
- Main rotor hub impact model validation (Section 3.4.5.4)
- Main rotor hub impact assessments (Section 3.4.5.5)

3.4.5.1.7   Note that it is assumed that it would be feasible to gain access to aircraft hardware for destructive impact testing and that sufficient structural design information could be sourced to enable theoretical models to be developed. These are significant assumptions and there is a risk that difficulties will be encountered gaining access to suitable specimens and basic design information.

3.4.5.1.8   If test specimens and/or design data is not available then the approach to assessing rotor, hub or propeller vulnerabilities may need to be revisited.

3.4.5.1.9   If serviceable aircraft components are not available (or would be prohibitively expensive) then retired (unserviceable) components could be used provided that they are not damaged in regions that may be critical to the testing. If no hardware is available for test then these Work Packages need to be reworked to remove the testing and validation elements.

3.4.5.1.10 However, if design data is not readily available then non-destructive surveying techniques and/or sectioning could be used to determine the geometry of example components and assumptions could be made about material grades and properties based upon knowledge of aerostructures.

3.4.5.2   Work Package WP-CA-R-T1: Rotors - Tail Rotor impact FE model generation and validation

3.4.5.2.1   The workflow for WP-CA-R-T<1-2> is shown in Figure 3-10.

3.4.5.2.2   The aim of this WP will be to create and validate FE models of UAS components impacting upon a tail rotor blade, and provide confidence in the use of FE modelling for subsequent prediction of the damage levels for specified tail rotors. This will require appropriate test specimens and relevant design data to be supplied.

3.4.5.2.3   Physical impact testing will be carried out, using UAS components against a static tail rotor blade to aid in determining damage levels. The testing will be carried out at velocities relating to the tip speed during take-off/high power conditions and the closing

speeds of the aircraft and UAS. The outcome will provide validation "points" for a typical tail rotor.

3.4.5.2.4   As well as recording the impacts with high-speed video and evaluating the level of damage sustained post-test, instrumentation should also be included to record transient deflections of the rotor blade as this will provide useful evidence for comparison with FE modelling results.

3.4.5.2.5   The aligned FE modelling activity will develop upon current best-practices to predict the level of damage caused to the rotor blades, which may include a combination of metallic, composite and structural honeycomb/foam components. The experimental results will allow development of the modelling methods, which can then be used to assess a wider range of rotor impact scenarios.

3.4.5.2.6   The FE models developed will be used to predict the effect of tail rotor impacts by each of the four UAS Threat Models. These results will provide additional evidence to inform IEAs for tail rotors.

3.4.5.3   Work Package WP-CA-R-T2: Rotors - Tail Rotor Impact Assessments

3.4.5.3.1   This activity doesn't include any additional testing but exploits the modelling methods developed in WP-CA-R-T1 to predict the response of two additional tail rotor designs to impacts by each of the four different UAS Threat Models.

3.4.5.3.2   Engagement with the engine OEM(s) is assumed in order to efficiently obtain sufficient details to make accurate assessments of UAS impacts. However, if this is not possible then it would be necessary to undertake surveys and research materials data, in order to approximate a specific rotor blade design or develop a generic, but representative, configuration.

3.4.5.3.3   Model generation and analysis of UAS impacts (four mass classes) against two tail rotor targets will be carried out, at two strike positions (hence two impact velocities) to determine damage levels.

3.4.5.3.4   The results of the WP will be used to populate the EASA Impact Effect Assessment, to classify the effect (i.e. High, Medium, Low).
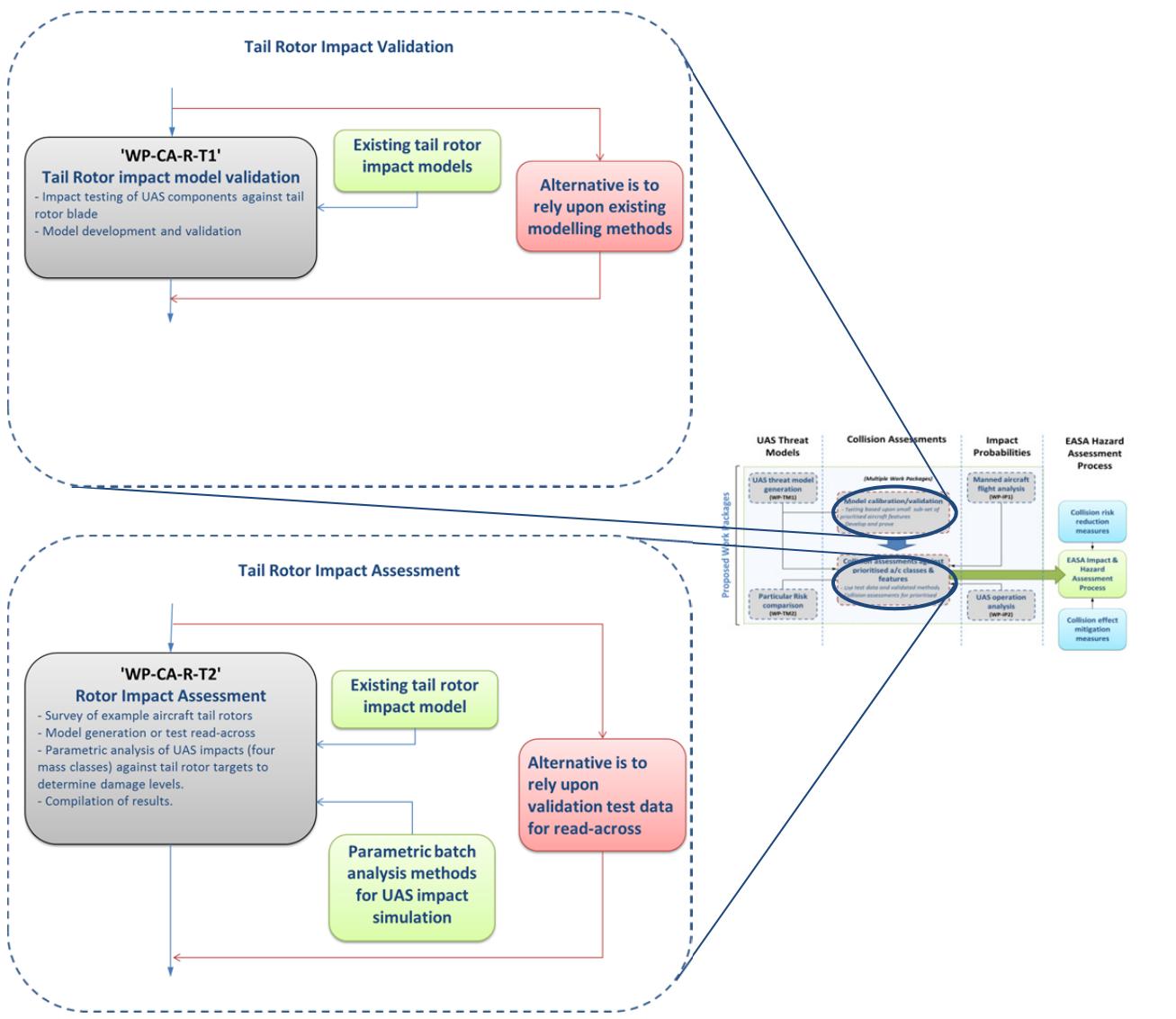
Figure 3-10: Tail rotor feature assessment workflow

3.4.5.4 Work Package WP-CA-R-H1: Rotors – Main rotor hub impact FE model generation and validation

3.4.5.4.1 The workflow for WP-CA-R-H<1-2> is shown in Figure 3-11.

3.4.5.4.2 The aim of this WP will be to generate test data to develop and validate FE models of UAS components impacting upon a main rotor hub, containing swash plate, pitch and teeter hinges, and pitch linkages. This will provide data to inform IEAs and also provide confidence in use of the modelling for subsequent prediction of the damage levels for main rotor hub areas.

3.4.5.4.3 Physical impact testing will be carried out, using UAS components against main rotor hubs to aid in determining damage levels; this will require appropriate test hardware to be

sourced for configurations of interest[14]. Impacts will be carried out against the perceived most vulnerable areas (likely to be the linkages, or hinge to the linkage). The impact velocities will be determined either by reference to the performance specification of the manned aircraft and UAS or via outputs from WP-IP1 and/or WP-IP2.

3.4.5.4.4   The modelling activity will use data generated during the Threat Modelling activity ('WP-TM1') and a simplified representation of the hub linkages to simulate the test conditions and develop an understanding of likely failure modes and weaknesses.

3.4.5.4.5   Although the number of tests are likely to be limited by available hub components (four impacts are assumed for planning purposes), the modelling activity will expand this dataset to include impacts against each of the four UAS configurations.

3.4.5.5   Work Package WP-CA-R-H2: Rotors – Main rotor hub Impact Assessments

3.4.5.5.1   The activity doesn't include any additional testing but exploits the modelling methods developed in WP-CA-R-H1 to predict the response of two additional hub rotor designs to impacts by each of the four different classes of UAS.

3.4.5.5.2   Engagement with the engine OEM(s) is assumed in order to efficiently obtain sufficient details to develop accurate UAS impact FE models. However, if this is not possible then it would be necessary to undertake surveys and research materials data in order to approximate a specific rotor blade design or develop a generic, but representative, configuration.

3.4.5.5.3   Model generation and analysis of UAS impacts (four mass classes) against two tail rotor targets will be carried out, at two strike positions (hence two impact velocities) to determine damage levels.

3.4.5.5.4   The results of the WP will be used to populate the EASA Impact Effect Assessment, to classify the effect (i.e. High, Medium, Low).

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[14]   When sourcing test articles (rotor hubs), it will be necessary to consider constraints on test facilities such as the size of specimen that can be accommodated. This may require the hub assembly to be provided separately from the main fuselage and the provision of additional linkages to replace items damaged during test.
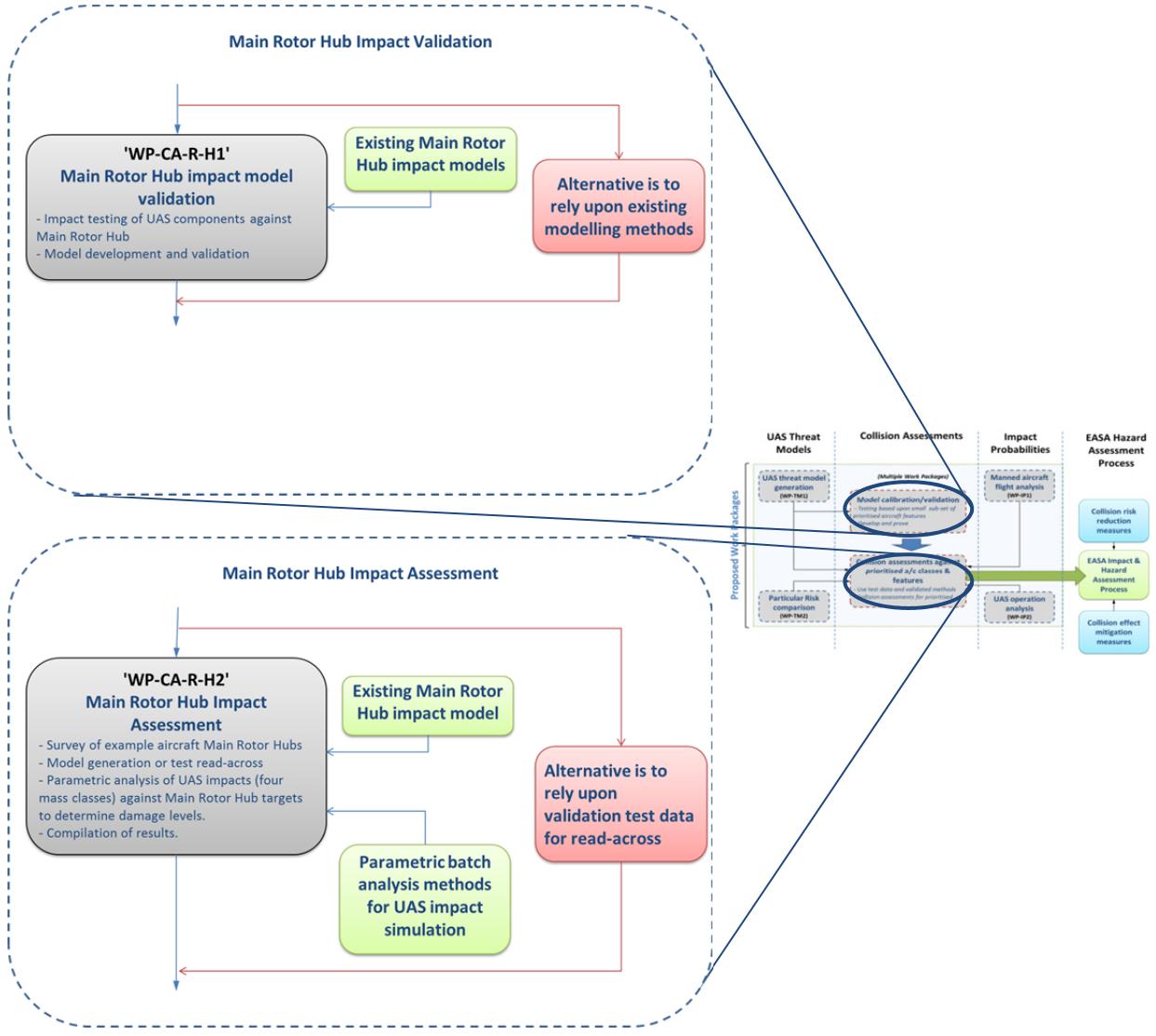
Figure 3-11: Rotor hub feature assessment workflow

3.4.6 Work Package WP-IEA1: EASA Impact Effect Assessment

3.4.6.1 This Work Package provides support to EASA in interpreting the data generated from the collision assessment work packages, and determining Impact Effect Assessments for a range of impact scenarios involving different aircraft types and UAS.

3.4.6.2 The process that will be followed to make these assessments is described in greater detail in Section 4.4 of the Work Area 2-5 report [4].

3.4.6.3 Also included in this Work Package is an activity to collate all of the evidence from previous Work Packages and put together a tool/repository that will help EASA to exploit the large volume of data generated to perform additional IEAs in the future and also add new data as it becomes available. This tool/repository should include provision for:

- Known UAS impact events (in-service examples or results from test).
- Comparison with Particular Risk certification requirements assessments.
- Results from feature-based tests.
- Results from validated FE on general features or specific structures.
- Results from previous IEAs

3.4.6.4   The scope of this Work Package is somewhat dependent on the volume of work realised in the preceding Work Packages and also the number of examples that EASA required support with.

3.4.7   Work Package WP-HEC1: EASA Hazard Effect Classification

3.4.7.1   The purpose of this WP is to support EASA in determining the final Hazard Effect Classification (HEC) at aircraft level, based on the predictive work of UAS threats against specified components and the resulting IEA.

3.4.7.2   The HEC at a/c level will be made utilising the EASA HEC definitions shown in Appendix VIII of [1]. Here a severity level (1-5) will be applied to the following:

- Effect on a/c;
- Effect on occupants (ex. Flight Crew);
- Effect on Flight Crew;
- Effect on Operations.

3.4.7.3   This task will not include any experimental or modelling activities, but will be an analytical and deductive task.

3.4.7.4   It is assumed that the HECs should be determined by a working group which could include representatives from aircraft manufacturers, operators, personnel involved with the testing and IEAs, and EASA. This WP acts as a placeholder for this working group.

3.4.7.5   The scope of this WP is highly dependent on the volume of work realised in the preceding WPs.

4 Phasing of research work

4.1 Introduction

4.1.1 The previous Section outlined a framework of Work Packages that would address EASA's requirement to understand the risks associated with collisions between UAS and manned aircraft.

4.1.2 The proposed work is intended to allow assessments to be made of collisions between multiple different mass classes of UAS and a broad range of manned aircraft, including large airliners, rotorcraft and General Aviation categories. This is achieved by conducting sufficient testing to provide read-across data and validation for modelling methods, which can be used to make informed assessments of a wide range of structural configurations.

4.1.3 However, the focus of immediate studies is on larger passenger aircraft (including fixed wing and rotorcraft) and adopts a phased approach. This Section proposes which of the Work Packages should be prioritised to make best use of phasing.

4.1.4 It should be noted that the proposed sequencing of Work Packages is just one illustration of how a future programme could be phased. However, the actual sequencing is likely to depend upon many factors which are currently not known, including budgetary, logistical, commercial and technical constraints.

4.1.5 It is also worth noting that the proposed phasing assumes that all activities will be undertaken and that additional prioritisation/down-selection is not required. If only a sub-set of the Work Packages could be funded then the phasing/prioritisation may be proposed differently. For example, the metallic panels activity may be removed in favour of the composite and sandwich panel tasks, since these materials are considered to be more susceptible to damage due to impacts with hard objects.

4.1.6 Furthermore, it is likely that results from early activities will influence plans for later Work Packages, so it will be beneficial to maintain a level of adaptability and flexibility in future plans.

4.1.7 The proposed phasing is shown as a roadmap below in Figure 4-1, assuming that each phase are 12 months in duration[15]. This is followed by a brief description of the activities in each phase.

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[15] 12 month phases were selected to align with annual budgetting cycles, but shorter durations could be adopted in order to separate activities into more phases.
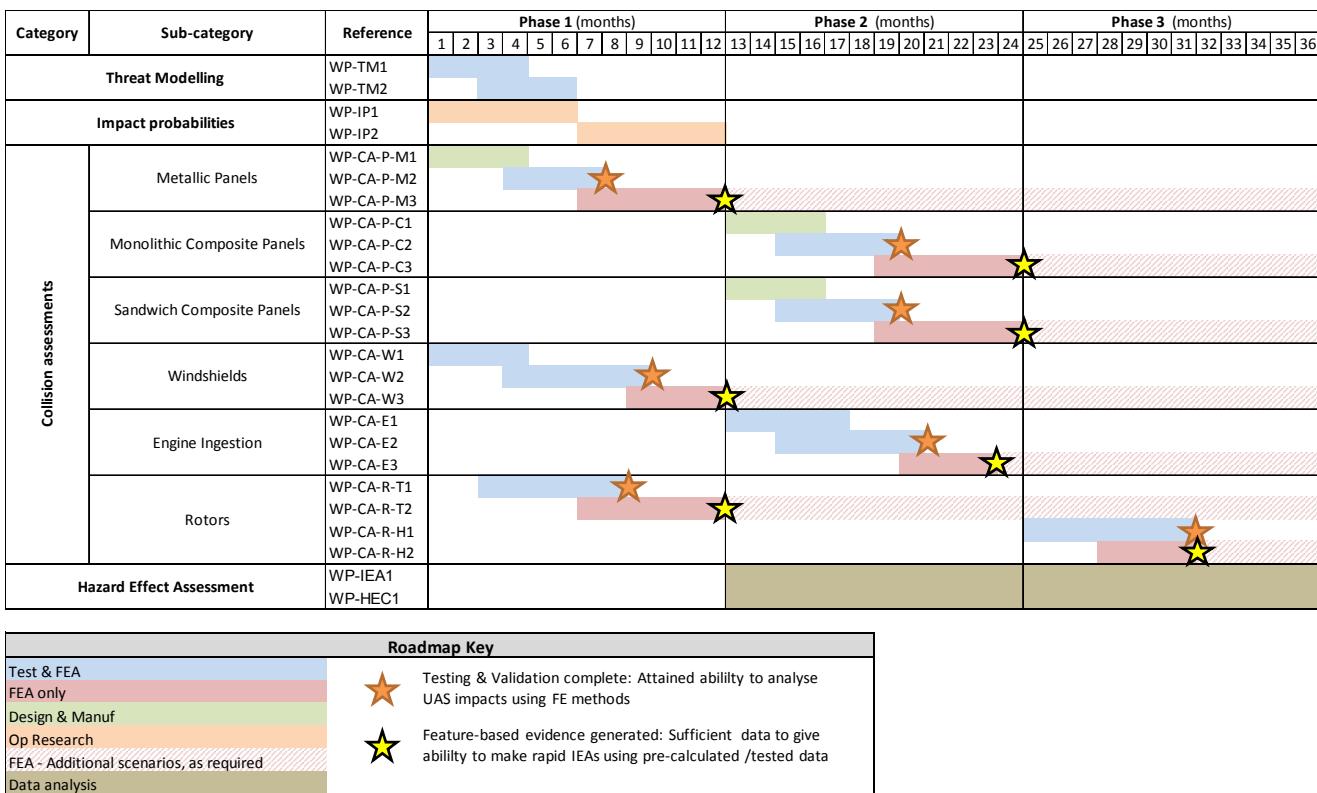
Category	Sub-category	Reference	Phase 1 (months)	Phase 2 (months)	Phase 3 (months)
Threat Modelling		WP-TM1			
		WP-TM2			
Impact probabilities		WP-IP1			
		WP-IP2			
Collision assessments	Metallic Panels	WP-CA-P-M1			
		WP-CA-P-M2			
		WP-CA-P-M3			
	Monolithic Composite Panels	WP-CA-P-C1			
		WP-CA-P-C2			
		WP-CA-P-C3			
	Sandwich Composite Panels	WP-CA-P-S1			
		WP-CA-P-S2			
		WP-CA-P-S3			
	Windshields	WP-CA-W1			
		WP-CA-W2			
		WP-CA-W3			
	Engine Ingestion	WP-CA-E1			
		WP-CA-E2			
		WP-CA-E3			
	Rotors	WP-CA-R-T1			
		WP-CA-R-T2			
		WP-CA-R-H1			
		WP-CA-R-H2			
Hazard Effect Assessment		WP-IEA1			
		WP-HEC1			

Roadmap Key

- Test & FEA
- FEA only
- Design & Manuf
- Op Research
- FEA – Additional scenarios, as required
- Data analysis

⭐ (orange) Testing & Validation complete: Attained abililty to analyse UAS impacts using FE methods

⭐ (yellow) Feature-based evidence generated: Sufficient data to give abililty to make rapid IEAs using pre-calculated /tested data

Figure 4-1: Proposed roadmap with phasing of Work Packages

4.2 Phase 1

4.2.1 Priorities for Phase 1 of a UAS collision programme are proposed as following:

4.2.2 Threat Modelling

4.2.2.1 The Threat Modelling task, 'WP-TM1' is considered to be a priority as it provides fundamental data that will be used for all collision assessments. As noted in Section 3.2.2, this task may be accelerated and the testing de-scoped if existing relevant Threat Models are utilised.

4.2.2.2 The Particular Risk comparison task, 'WP-TM2' should also be included within Phase 1 as evidence from this activity will allow direct comparisons to be made with existing Particular Risks. If it can be shown that some UAS impact conditions are enveloped by current certification requirements then this may provide early results for EASA's IEA matrix.

4.2.3 Impact Probabilities

4.2.3.1 The inclusion of the manned aircraft flight analysis Work Package, 'WP-IP1' in Phase 1 is recommended as it provides aircraft velocity data that can be used to aid the completion of IEAs in Phase 2.

4.2.4 Ideally, the UAS operational analysis task, 'WP-IP2' would also be included in Phase 1 as it will also provide data to inform impact velocity assumptions for IEAs. Furthermore, it is possible that analysis may determine that some classes of UAS should be excluded from

certain impact scenarios due to minimal likelihood of them being operated at altitudes where manned aircraft might be expected.

4.2.5   Collision Assessments

4.2.5.1   It is proposed that the metallic panels work packages ('WP-CA-M1', 'WP-CA-M2' and 'WP-CA-M3') should be included in Phase 1 as these will provide baseline data that can be used to assess a wide variety of high priority manned aircraft features such as Leading Edges and frontal fuselage structures. It is anticipated that these tests will be biased towards large passenger aircraft configurations rather than General Aviation classes.

4.2.5.2   Note that this prioritisation of metallic panels reflects the prevalence of metallic structures in current large aircraft. It also represents an incremental approach to the development and validation of UAS collision models, as composite structures exhibit more complex failure modes than aluminium alloys. The addition of composite specimens in Phase 1 would depend upon available budgets.

4.2.5.3   Although the windshield activity is a significant undertaking, it has been prioritised to reflect the criticality of windshields in protecting the flight crew, maintaining pressurisation (where applicable) and maintaining visibility. The windshield constitutive model validation activity ('WP-CA-W1') should be therefore be undertaken, followed in sequence by impact testing of screens and associated modelling work in 'WP-CA-W2' and 'WP-CA-W3'.

4.2.5.4   Tail rotors are also perceived to represent a critical vulnerability for rotorcraft and so have been prioritised. Impact model validation activity ('WP-CA-R-T1') should be initiated to provide test data to validate existing rotor blade modelling methodologies and this should be expanded to cover additional rotor examples in 'WP-CA-R-T2'.

4.3   Phase 2

4.3.1   Priorities for Phase 2 of a UAS collision programme are proposed as following:

4.3.2   Threat Modelling

4.3.2.1   Completed in Phase 1 (subject to requirements for incremental updates)

4.3.3   Impact Probabilities

4.3.4   Completed in Phase 1 (subject to review should UAS usage be perceived to change significantly)

4.3.5   Collision Assessments

4.3.5.1   Composite panels studies (monolithic and sandwich) should be completed, based upon configurations that are applicable to large aircraft.

4.3.5.2   Engine ingestion activities to be undertaken.

4.4 Phase 3

4.4.1 Priorities for Phase 3 of a UAS collision programme are proposed as following:

4.4.2 Threat Modelling

4.4.2.1 Completed in Phase 1 (subject to requirements for incremental updates)

4.4.3 Impact Probabilities

4.4.4 Completed in Phase 1 (subject to review should UAS usage be perceived to change significantly)

4.4.5 Collision Assessments

4.4.5.1 Impacts against Rotor Hubs

4.4.5.2 Expansion of modelling/analysis activities to cover other collision scenarios and provide 'fill-in' data where there is perceived to be a gap in knowledge.

4.4.5.3 Consideration of other impact regions such as propellers.

4.5 Beyond Phase 3

4.5.1 The proposed phases of work are subject to many assumptions and may require revision as knowledge is acquired, UAS designs and operations evolve, data is collected on UAS related incidents, and mitigations are put into place. Further research may therefore be required to keep up with technologies and usage trends.

4.5.2 The structure of the proposed programme of work is intended to enable flexibility and adaptability in the event of changes to the 'threat profile'. If, for example, a new configuration or class of UAS became popular e.g. fixed wing or alternative multi-rotor design/mass class, then this could be accommodated as an update to the threat models and re-runs of the validated FE-based collision models.

4.5.3 In all cases, it is assumed that research would be focussed upon establishing the likelihood and consequences of mid-air collisions.

5　References

1. *'Drone Collision' Task Force Final Report*, EASA, 04 Oct 2016.

2. *Research programme on collisions with UASs*, EASA, EASA.2016.LVP.50, Oct 2016.

3. David Bush, *Detailed Project Plan (D1) Research Programme on Collisions with UASs - Version 1*, QinetiQ, QINETIQ/17/00621, 15th February 2017.

4. Austen, W., Research Programme on Collisions with Drones: Work Areas 2-5 Final Report (D4), QinetiQ, QINETIQ/17/01545/1.0, 19 Jul 2017.

5. *Drone Safe* dronesafe.uk/drone-assist/, 11th May 2017.

6. *Virginia Tech News*https://vtnews.vt.edu/articles/2015/10/102815-engineering-jetenginedronestrike.html, 14th May 2017.

7. *Civil Aviation Authority* www.caa.co.uk/Data-and-analysis/Safety-and-security/Datasets/Birdstrikes/, 11th May 2017.

8. *Small Remotely Piloted Aircraft Systems (Drones): Mid-Air Collision Study*, UK DfT/ MAA/BALPA/UASCDC/QinetiQ, 22nd July 2017.

6   List of Abbreviations

A/C *or* a/c	Aircraft
COTS	Commercial Off-The-Shelf
CS	Certification Specification
EASA	European Aviation Safety Agency
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Model
FRP	Fibre Reinforced Plastic
HEC	Hazard Effect Classification
IEA	Impact Effect Assessment
MAC	Mid-Air Collision
NATS	National Air Traffic Control Services
OEM	Original Equipment Manufacturer
PR	Particular Risk
RPM	Revolutions Per Minute
UAS	Unmanned Aircraft System
WA	Work Area
WP	Work Package

A   Model nomenclature

A.1   This appendix provides a glossary of the terms and language used, in this report, around the use of 'models', 'modelling' and 'modelling methods'.

Model term	
General	Mathematical or Finite Element (FE) representation of a system
'Material model'	Analytical description of the behaviour of a material under load e.g. stress-strain curve. These will be developed through crush (compression) testing and impact testing. *e.g. Material model (defining the material behaviour under load and impact conditions)*
'Threat Models'	FE representation of each class of UAS. This will include major components that will utilize the material models developed from tests. *e.g. Threat Model (FE model of threat configurations, using the developed material models for the principal components)*
'Collision assessment models'	FE simulation of the UAS Threat Model impacting real or representative aircraft components. *e.g. Collision assessment model (FE model of collision event between UAS threat (model) and manned aircraft component.*
Modelling	The act of developing or running models (mostly FE in this context)
Modelling methods	The underlying approach used to construct the (FE) models. This may include parameters such as element selection, meshing approach, contact formulations, material failure laws etc.

Table A-1: Glossary of terms relating to model description

C   Example of proposed collision assessment process

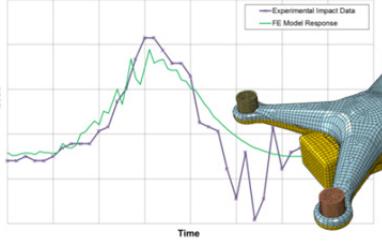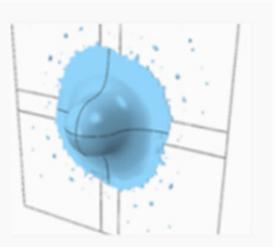**Proposed Collision Assessment Process**

D   Work Package descriptions

D.1   The Work Packages are presented in Section 3. The follow pages give a brief description of each, along with their benefits, precedents, dependents, inputs, outputs, and where applicable, possible alternatives.

D.2   Note that these descriptions do not include description of project co-ordination activities or risks.

WP No.		
WP-TM1		
(EASA.2016.LVP.50-WA2)		

UAS Threat Models - UAS Threat Model Generation

Description

The purpose of the WP is to develop validated FE based Threat Models of each of the four classes of UAS Quadcopters i.e. 'Harmless', 'Small', 'Medium', 'Large'. This follows a process of component testing, component model calibration, and assembly of component models into Threat Models of the complete UAS.

Testing of UAS components: Static crush and dynamic impact tests of UAS components (motors, batteries, cameras) should be conducted to obtain material behaviours under impact conditions. This requires tests to be carried out for the components of different classes of UAS.

Tests to be carried out in the axis of perceived impact. If unknown, then tests in different axes systems are to be carried out which may result in an anisotropic material model.

Tests will involve (per axis): 1 static crush in a suitable, calibrated test machine; and up to 2 dynamic tests against a calibrated instrumented Hopkinson bar (or appropriately accurate alternative), at different impact velocities. The impact velocities are TBD but one should be aligned with the typical velocities used for certification against other Particular Risks such as birdstrike.

For the impact tests, the Lithium batteries must be fully charged in order to provide information of their non-structural behaviour, i.e. do they ignite or explode? Any suppliers undertaking this work must acknowledge that they understand this risk and have accounted for it in their test conduct.

All static tests should be captured using standard video and impact tests should be recorded using high speed video. Still images must also be supplied of experimental arrangements and specimens (pre- and post-test).

Calibration of component theoretical models: Data from the testing shall be processed and used to characterise homogenised material models (isotropic or anisotropic) for each UAS component. This material calibration process will be iterative and will include FE modelling of the crush and impact tests to confirm that the resultant component representations perform correctly under load. The outcome of this work will be FE representations of each of the UAS components that have been tested.

Generation of UAS Threat Models: The UAS components should be assembled into UAS Threat Models. These models should include appropriate representation of other major components, including the airframe and other significant items; this may require generation of additional components and research/testing to determine appropriate materials data, including failure laws. Joints between components should be considered and the complete UAS Threat Models should be demonstrated in an example impact analysis.

Benefits

Results will allow complex components to be represented as simplistic primitive FE geometries with characterised material models, defining the stiffness, elastic-plastic and strain-hardening behaviours. This negates the need to model the detail of components (such as the steel spindle, the aluminium casing and the copper winding of a motor), which would be prohibitively computationally expensive.

A component database will be established, allowing different configurations of UAS to be modelled as required.

The four classes of UAS Quadcopters will be developed for use in later FE-based collision assessments.

Evidence will be generated from the battery tests to indicate whether there is a significant risk of fire or explosion from UAS batteries.

Precedents

None

Dependents

The other WPs which involve modelling of the MAC are dependent on this WP. i.e. WP-TM1, WP-CA-P-M/C/S2; WP-CA-P-M/C/S3; WP-CA-W2; WP-CA-W3;WP-CA-E2;WP-CA-E3, WP-CA-R-T1; WP-CA-R-T2, WP-CA-R-H1, WP-CA-R-H2. The UAS configurations defined within this WP will also support WP-IP2 and WP-IEA1.

Inputs

Agreement with EASA of UAS configurations and FE codes

UAS components, nominally as per Table 3-1.

Outputs

Four-off validated FE UAS Threat Models that can be used in subsequent dynamic explicit impact simulations.

Technical note outlining the process and results of this WP, including:

 - Database of FE component models with characterised material properties.

 - Observations on the volatility of batteries under crush and impact conditions.

High speed video footage of impact tests.

Gearing / Alternatives / Scalability

This WP may be supplemented and enhanced with existing data on similar work already carried out on UAS components.

Additional benefits can be gained by combining the results of this WP with data from WP-TM2, where UAS component response can then be compared to Particular Risk responses and can thus be compared to existing certification against these Particular Risks.

This WP and WP-TM2 satisfy Recommendations 1 and 2 from the EASA Task Force Report [1].

Assumptions

- Each component will only be tested in one axis. This will be selected based upon the most likely axis of impact.
- The modelling activities must be well aligned with later collision modelling tasks (see Dependents) as care must be taken throughout to ensure that the Threat Models are fit for purpose. This should include consideration of the robustness of the model under destructive impact conditions and also the computational requirements (including stable time increment), as the Threat Models will later be integrated into more complex collision models, including detailed target structures.
- The procurement of UAS components is included within this task.

WP No. WP-TM2 (EASA.2016.LVP.50-WA2)		

UAS Threat Models - Particular Risk Comparison

Description

The purpose of this WP is to understand how currently certified threats (e.g. Hail, Bird, Engine fragments) compare to the uncertified threat of drone components in order to establish some read-across of data.

Testing of Particular Risks (PRs):

Dynamic impact tests of PRs (Hail (3 sizes), Bird (2lb and 4lb), Engine fragments (3 sizes)) should be performed to obtain force-time responses under impact conditions.

These tests will be against instrumented Hopkinson bars (or equivalent), at different impact velocities, one of which will be typical of current certification requirements and the other is TBD.

All impact tests should be recorded using high speed video. Still images must also be supplied of experimental arrangements and specimens (pre- and post-test).

Comparison to UAS component impact data: Data from the testing in WP-TM1 shall be compared to dynamic test data from this WP in order to assess whether the UAS component threat is less severe, equivalent or more severe than the PR threat data; this will consider the combination of the impulse (area under the force-time curve), the mass and impact velocity of the threat.

Benefits

Results from this activity may enable IEAs for some UAS threats and impact regions to be inferred by reference to existing standards and certification tests. This would provide early results and reduce the need for additional testing and modelling work under the Collision Assessment WPs.

Precedents

This WP requires the output from WP-TM1 to make the comparisons.

Dependents

Results may allow the scope of other WPs, which involve modelling of the MAC, to be reduced.

It may also be possible to make some IEAs by reference to existing certification standards.

The other WPs which would benefit from this WP include WP-CA-P-M/C/S2, WP-CA-P-M/C/S3, WP-CA-W2, WP-CA-W3, WP-CA-E2, WP-CA-E3, WP-CA-R-T1, WP-CA-R-T2, WP-CA-R-H1 and WP-CA-R-H2.

Inputs

Agreement with EASA of PR projectiles and typical certification velocities for platforms of interest.

UAS component impact test results from WP-TM1.

Outputs

Technical note including:

- Description of the tests and
- Comparison of results with UAS components, identifying opportunities to demonstrate that existing certification standards will envelope UAS impact threats.
High speed video footage of tests.

Gearing / Alternatives / Scalability

Assumptions
• Assumed that this WP is contracted at the same time as WP-TM1, using the same experimental arrangement.

WP No. WP-IP1 (EASA.2016.LVP.50-WA5)		

Impact probabilities - Manned Aircraft Flight Analysis

Description

This WP will provide a probabilistic understanding of operating behaviours of different classes of manned aircraft. The output of this WP will be aimed at understanding the probabilities and severities of collisions with UAS and the perceived benefits of enforcing altitude limits and/or localised geo-fencing.

Tasks within this activity include:

- Sourcing historical European manned flight data records (large, statistically meaningful body of data required, ideally covering up to 1 year of flights across Europe as this will account for regional and seasonal effects).

- Processing of the data to determine probabilistic distribution of true air speeds with altitude (up to 10,000ft), for each class of aircraft.

- A statistical basis for this data should be agreed with EASA e.g. mean or 90th percentile, and applied to the processed data. This will determine velocity figures, by aircraft class, for collisions at different altitudes.

- The data should also be processed to assess the distribution of flights operating at different altitudes away from their departure and arrival airports. This would provide evidence to assess the effectiveness of different sized 'UAS exclusion zones' around airports.

Benefits

The work will provide a means to determine the likely effectiveness of potential measures to limit the locations and altitudes at which UAS can operate as a means to increase aviation safety. It will also provide statistical data to determine the probable (rather than maximum) speeds at which collisions may occur for various classes of manned aircraft. This will aid in determining the likely range of MAC velocities for the collision assessment WPs.

The velocity data from this study would also have relevance to bird strike assessments.

Precedents: None

Dependents

The velocities determined through this exercise will benefit the following WPs:
WP-CA-P-M/C/S2, WP-CA-P-M/C/S3, WP-CA-W3, WP-CA-E2, WP-CA-R-T1, WP-CA-R-T2, WP-CA-R-H1, WP-CA-R-H2, WP-IEA1, WP-HEC1.

Other data will support decisions by EASA on effective measures to mitigate collision risks.

Inputs

Data relating to operating behaviours of manned aircraft.

Outputs

Technical note outlining:

- Description of activity and methods used

- Results and discussion of the velocity vs. altitude activity

- Results and discussion of the airport proximity study

Gearing / Alternatives / Scalability

If this activity is not funded during initial phases of a UAS collision assessment programme then it would be necessary to estimate aircraft speeds at credible altitudes.

This WP, when combined with WP-IP2, would provide data to allow the probability and velocity of MACs to be assessed. This would provide very useful data when considering how to manage collision risks.

As an alternative to procurement of historical data, it could be gathered via Europe-wide monitoring of aircraft movements. However, this would require a period of time to gather a significant amount of statistical information which accounts for seasonal variations.
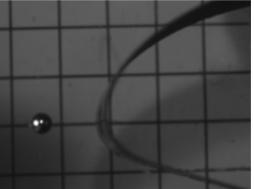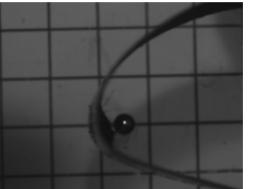
Assumptions

- It is currently assumed that historical flight data would be procured within this task. This would nominally include a year's worth of flight data covering Europe in order to capture regional, diurnal and seasonal variations. If EASA or other stakeholders have access to this data and can provide it free-of-charge then savings could be made to the WP cost.
- It is also assumed that the quality of data is sufficient to make appropriate assessments and that anomalous results can be readily filtered out.

WP No. WP-IP2 (EASA.2016.LVP.50-WA5)		

Impact probabilities - UAS Operation Analysis

Description

This WP will provide greater understanding of the operating behaviours of UAS pilots. The output of this WP should include analysis of probable operating velocities and altitudes for each of the four UAS classes identified.

The activities to meet this objective will depend upon the availability of relevant data but could include:

- Performance limitations, practical usage limitations and software-based restrictions imposed on UAS

- Analysis of reported incidents

- Survey of UAS ownership and usage

- Flight plans and licenses for commercial operators

- Data collected through voluntary apps such as the UK National Air Traffic Control Services (NATS) 'Drone Assist'

The results from this WP will be used with data from WP-IP1 to determine the bounds of probable impact velocities; this will be used in IEAs.

Benefits

Analysis of the capabilities and behaviours of each class of UAS will provide information that can be used to justify assumptions about the likelihood and velocities of potential collisions.

It is possible that this analysis may enable some collision scenarios to be ruled-out as being highly unlikely, so that attention can be focused upon more probable occurrences.

Precedents

Agreement of UAS threat configurations from WP-TM1.

Dependents

Velocity ranges can be determined to an agreed statistical basis for collision assessments: WP-CA-P-M/C/S2, WP-CA-P-M/C/S3,WP-CA-W2 WP-CA-W3, WP-CA-E2, WP-CA-E3, WP-CA-R-T1, WP-CA-R-T2, WP-CA-R-H1, WP-CA-R-H2, WP-IEA1.

Inputs

- UAS threat configurations/classes defined in WP-TM1.

- Usage data for UAS operations (if available).

Outputs

Technical note outlining:

- Details of research activities.
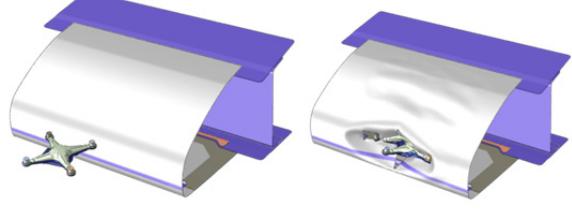
- Discussion of risks associated with different types of user e.g.

commercial/research/recreational/competition/etc. and UAS classes.

- Recommendations of probable velocities and altitudes for each class of UAS Quadcopter.

Gearing / Alternatives / Scalability

This WP, when combined with WP-IP1, would provide data to allow the probability and velocity of MACs to be assessed, thereby inputting to risk management processes.

Assumptions

- It is assumed that if quantitative user data cannot be made available then this activity will rely upon a more qualitative assessment. This may include observational data and practical experience plus a review of hardware, software and practical flight limitations. This would still provide a justifiable basis upon which to make assumptions about the likelihood and severity of MACs.

| **WP No**.

WP-CA-P-M/C/S1

Same process for metallic (M), monolithic composite (C) and sandwich composite (S)

(EASA.2016.LVP.50-WA3) | | |

Panel Impact Validation - Design and manufacture of test panels & fixture

Description

The objective of this WP is to design and manufacture panel test specimens that can be used for impact testing. This WP description is valid for metallic (M), composite (C) and sandwich (S) panel specimens.

Design & Manufacture

A set of seven (nominal quantity) simple curved panels in a Leading Edge-style fixture should be designed and manufactured using each material configuration. It is assumed that the metallic, composite and sandwich panel designs will be based upon the same basic design and that they will share common interfaces with the support fixture. However, the panel thicknesses may be different for each material type in order to reflect example components.

As a starting point, the panels are expected to be in the order of 500mm in length and 200mm in depth. However, the final dimensions should be determined based upon a more detailed review of aircraft designs (e.g. CS-25/CS-23 outer wing/winglet/empennage leading edge) so that the configuration that is being used for FE model development and validation purposes is broadly similar to examples of primary interest. On this basis it is suggested that the test specimen thickness (and supported length) be somewhere between the thickest and thinnest examples.

Note that the above image is for illustration purposes only and the proposed test configuration would require a more supportive fixture, with riblet-like stiffening at each end.

Benefits

This design and manufacture WP will allow control over the design, including the geometry, support conditions and materials; this reduces the number of unknowns and the complexity of the modelling for calibration/validation purposes.

Multiple simple panels can be manufactured to identical standards without needing to source genuine aircraft components.

As well as providing validation evidence, the panel configurations can be chosen to provide information that enables initial IEAs to be made.

Precedents

None

Dependents

This WP feeds into WP-CA-P-M/C/S2 which involves physical tests carried out against these panels.

Inputs

Advice and guidance should be sought from aircraft OEMs/suppliers to ensure that manufactured panel features are of appropriate materials and dimensions. If this is not possible then assumptions would need to be made based upon knowledge of aerostructures.

Outputs

Series of curved panels ready for testing: metallic (M), monolithic composite (C) and sandwich composite (S) with accompanying certificate of conformity.

Technical note describing design and construction of panels, including interface requirements.

Gearing / Alternatives / Scalability

An alternative to this WP might be the sourcing of real panel components from aircraft manufacturers. Whilst this has the benefit of unambiguously representing genuine aircraft structure, it is envisaged that there would be greater difficulties sourcing sufficient components of the same type, the structure is likely to be more complicated and would require a detailed geometric survey for model validation, and testing times are likely to be longer due to unwieldy test specimens.

If necessary the number of impact conditions and panel materials/configurations can be tailored to available resources. However, it should be noted that a reduced test matrix would result in less-thorough validation of methods and therefore a greater level of technical risk.

If the proposed programme is not affordable then consideration could be given to using simpler flat panels for one or more material types. This would still provide validation evidence for FE models but the tests results themselves may not be as directly relevant to existing aircraft structures.

Assumptions

- Basic example design data can be supplied by aircraft OEMs/major suppliers. This will be for the purpose of tailoring the panel designs to configurations of interest. An alternative would be to either undertake surveys of example aircraft or make assumptions based upon industry knowledge and published data.
- The activity would need to be coordinated closely with WP-CA-P-M/C/S2 and WP-CA-P-M/C/S3.

WP No.		
WP-CA-P-M/C/S2		
Same process for metallic (M), monolithic composite (C) and sandwich composite (S)		
(EASA.2016.LVP.50-WA3/4)		

Panel Impact Validation - Testing and model calibration

Description

The objective of this WP is to undertake impact testing against each of the different test specimens in order to generate data that can be used to: develop and validate FE modelling methods, and; enable initial IEAs to be made. This WP description is valid for metallic (M), composite (C) and sandwich (S) panel specimens.

Testing

Physical impact testing will be conducted using UAS components or whole UAS assemblies against manufactured panels to aid in determining threshold penetration velocity. The outcome will provide validation "points" for each class of panel.

Up to seven impacts are assumed, using two different impactor types. The proposed work assumes between three and four shots in each configuration in order to experimentally determine a range of damage and threshold penetration velocities.

Witness plates (or similar) should be used behind the test specimen to provide an indication of the severity of any secondary impacts once the panel has been penetrated.

All impact tests should be recorded using high speed video. Still images must also be supplied of experimental arrangements and specimens (pre- and post-test).

For the composite panels, post-test non-destructive examination (NDE) or sectioning of specimens should be conducted to establish the extent of damage.

Modelling

The modelling activity should use current best-practice for impact modelling against aircraft structures (composite and metallic). FE models of the test specimens should be developed and run prior to testing in order to predict panel failure velocities; this will be used to inform the initial velocities and impact locations used in each test configuration.

Data from the test results should be used to develop the models, though calibration of input values such as material strengths should be maintained within credible values.

Comparisons should be made between the final FE results and test evidence. Assuming that an acceptable correlation is achieved, then the validated models can be used with confidence in further, more complex, simulation activities.

Benefits

Validation of modelling methods for predicting the effect of collisions between UAS and widely-used panel structures on manned aircraft.

Provides the ability to confidently and efficiently predict threshold penetration velocities for multiple UAS mass classes against the applicable family of panels.

Precedents

The physical testing in this WP relies on the manufacture of physical panels from WP-CA-P-M/C/S1.

The modelling activity in this WP relies on successful and accurate UAS component material

characterisation carried out in WP-TM1.

Collision likelihood and velocity data from WP-IP1 and WP-IP2 (optional).

The test activities may also be guided by output from WP-TM2 (optional).

Dependents

This WP feeds into WP-CA-P-M/C/S3 which involves prediction of threshold velocities for different classes of panels against collision with different classes of UAS. It also provides initial indication of the vulnerability of a small number of different panel configurations for IEAs.

The results from this activity also contribute to WP-IEA1 and therefore WP-HEC1.

Inputs

Series of curved panels plus their materials data and geometry: metallic (M), monolithic composite (C) and sandwich composite (S) from WP-CA-P-M/C/S1.

UAS Threat Models and component models from WP-TM1.

Agreement of impact cases, including component types and velocities for first tests. If completed, this may be influenced by WP-IP1, WP-IP2 and WP-TM2 (optional).

Outputs

Technical note including:

- Description and images of test set-up
- Test results
- NDE results
- Details of model development and calibration activities
- Comparison of final results with test data

Validated FE models of impact tests.

High speed videos of all impacts.

Gearing / Alternatives / Scalability

An alternative to this WP and WP-CA-P-M/C/S1 is to rely upon existing impact modelling methods without the validation step and without the confidence in further modelling activities. The risk associated with not performing this step is that FE-based results would not be validated against UAS impact threats and may therefore be of low accuracy and be open to greater challenge. This risk is judged to be greater for the composite and sandwich panel classes where methods are less mature than for metallic panels, due to the increased complexity of the failure modes.

Assumptions

- The activity would need to be coordinated closely with WP-TM1, WP-CA-P-M/C/S1, and WP-CA-P-M/C/S3.

WP No.		
WP-CA-P-M/C/S3		
Same process for metallic (M), monolithic composite (C) and sandwich composite (S)		
(EASA.2016.LVP.50-WA4)		

Panel Impact Validation - Panel Feature Assessments
Description
The aim of this WP (or WPs, when considering the different material options), is to exploit the validated modelling methods developed within WP-CA-P-M/C/S2 to undertake a series of impact assessments using different target configurations in order to build up a database of results that can be referenced when conducting IEAs. No testing is involved and it is purely an analysis task.
Modelling
Using knowledge gained through the previous WPs, coupled with a more detailed survey of aircraft structures, a range of common/generic panel features across a/c classes should be designed.
FE models of the panel configurations should be generated and parametric analysis of UAS impacts (four mass classes) completed to determine threshold penetration velocities. It is nominally assumed that up to eight different combinations of panels and impact location/angle should be included, with each configuration being assessed against the four classes of UAS Quadcopter. However, it is also assumed that this analysis matrix can be reduced by limiting the maximum impact velocities and omitting runs where a no damage or penetration result can be implied from other analyses. Whole UAS Threat Models should be used in each of these collision activities.
Results from the analyses should be compiled (including calculation of threshold velocities, video files and observations) in order to provide a dataset that can be referenced when assessing a wide range of features across different a/c types.
Benefits
Use of validated FE modelling provides an efficient means by which to generate relatively large volumes of collision data for a range of panel configurations and the four classes of UAS. The results from these analyses will allow IEAs to be made for a wide range of general panel-based features across multiple classes of manned aircraft.
Precedents
This WP relies on the model validation from WP-CA-P-M/C/S2 for confidence in the predictions; alternatively existing impact modelling methods without validation could be utilised (but this is not recommended).
The Threat Models from WP-TM1 are also required.
Dependents
Provides information to EASA Impact Effect Assessment (IEA) at a/c component level to classify the effect (High, medium low); carried out in WP-IEA1.
Inputs
Geometry / materials / assembly for range of common/generic panel features across a/c classes.
Validated FE models and technical notes from WP-CA-P-M/C/S2.

Threat models from WP-TM1.

Agreement of matrix of collision scenarios for evaluation; i.e. UAS / component vs panel feature. This may be influenced by WP-IP1 and WP-IP2 for credible UAS, aircraft and velocity combinations, and WP-TM2 which may allow some configurations to be pre-determined by comparison with existing certification tests.

Outputs

Technical note outlining:

- Panel/feature configurations

- Analyses completed and predicted penetration threshold results and damage levels for a matrix of scenarios (as per agreed analysis matrix).

Video (animation) files of each impact case should also be provided, along with any relevant notes to aid the interpretation of the data.
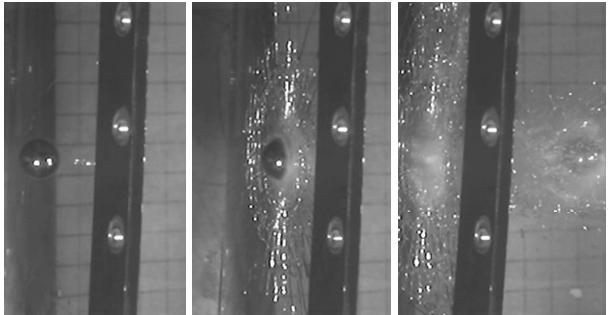
Gearing / Alternatives / Scalability

Data from testing in WP-TM1 (UAS components) and WP-TM2 (Particular Risks) may provide a means by which to de-scope this activity or focus it on configurations of greatest technical value.

The alternative to this WP is to rely upon the small amount of validation test data for read-across, but this would greatly limit EASA's ability to assess different configurations.

This WP contributes to Recommendation 3 from the EASA Task Force Report [1].

Assumptions

- Basic example design data can be supplied by aircraft OEMs/major suppliers. This will be for the purpose of specifying the panel configurations of interest. If not available then panels should be designed based upon basic surveys or as simple parametric examples.
- It is assumed that the panel configurations will be simple geometries with minimal parts and that they can be defined without the need for detailed surveys. If initial findings suggest that it would be desirable to increase the complexity of the panel designs then this would require greater levels of effort.
- This is a highly computationally-intensive activity involving hundreds of impact analyses across the three material types.
- The activity would need to be coordinated closely with WP-TM1, WP-CA-P-M/C/S1, WP-CA-P-M/C/S2, and WP-IEA1.

| **WP No**.

WP-CA-W1

(EASA.2016.LVP.50-WA3)		

Windshield Impact Validation - Constitutive materials validation

Description

The objective of this WP is to develop and compile reliable data on windshield materials (e.g. toughened glass, acrylics, PVB) that can be used with confidence in later windshield modelling activities.

Testing

Impact testing will be undertaken to generate experimental evidence for up to two glass/acrylic materials. This will use coupon/plate specimens sourced from windscreen manufacturers (see assumptions) and will include up to 6 impact tests to aid the development and validation of material models and selection of appropriate failure laws.

All impact tests should be recorded using high speed video. Still images must also be supplied of experimental arrangements and specimens (pre- and post-test).

Modelling

All tests should be simulated using FE models of experimental arrangements.

Research into material properties for windshields should be used to provide initial material properties and the results from the above tests should be used to refine these for up to two down-selected materials.

Benefits

The complex failure response of glass and other brittle materials, particularly when combined in laminated windscreens can be difficult to accurately model. This WP provides essential data that will de-risk the analysis of more-complex tests against full windshield structures in WP-CA-W2.

Precedents

None

Dependents

This WP feeds into WP-CA-W2, which involves analysis and physical tests carried out against aircraft windshields. It also informs FE modelling activities in WP-CA-W3.

Inputs

Agreement of aircraft windscreen that are of primary interest (propose CS-25, CS-23 (jet), CS-29, and CS-27).

Supply of glass plates / coupons

Property data for windshield materials

Outputs

Technical note outlining:

- Materials property data for windshield materials (including damage/failure characteristics)

- Test configurations and conduct

- Details of FE models

- Test results and comparison with FE methods
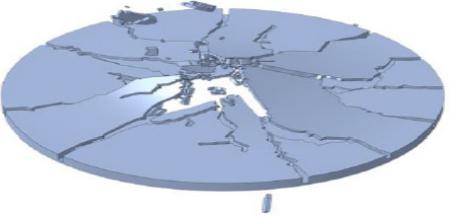
Validated FE models of experimental trials.

High speed video footage of test cases.

Gearing / Alternatives / Scalability

Alternative is to rely upon existing materials data from OEMs and/or other research establishments, provided that this can be made available for wider usage.

Assumptions

- Windshield materials can be sourced for impact testing. The size of the specimens is to be agreed.
- Up to two materials will be evaluated through impact testing.

WP No. WP-CA-W2 (EASA.2016.LVP.50-WA3/4)		

Windshield Impact Validation - Windshield model validation

Description

The objective of this WP is to generate a relatively large body of experimental evidence for impacts between UAS and up to three different aircraft windshield designs. This WP also includes the development of FE models that can be subsequently used to expand this further to consider additional designs and also alternative threats against the same designs.

This WP includes a greater element of testing than other WPs. This is to reflect the number of different types of screens in-service and their criticality to the safety of the crew and effective operation of the aircraft.

Testing

Physical impact testing should be conducted using sequences of components or whole UAS assemblies against laminated glass windshields to determine threshold penetration velocities. The outcome will provide validation "points" for three different classes of windshield; one of which should be from CS-25 (e.g. A320) and others from CS-29/CS-27/CS-23 classes.

At least three impacts are considered to be necessary for each UAS/aircraft combination to get an indication of penetration thresholds (more may be required if results demonstrate 'scatter'). A test matrix should be agreed as part of the task, which is assumed to include up to five sets of tests, using different combinations of the four UAS configurations (15 tests in total).

Due to the sensitivity of the brittle windshield materials to global deformations (and therefore support conditions), if the testing is to be representative of genuine impacts then the screens should be installed in a section of fuselage for testing. It will therefore be necessary to source appropriate fuselage components as well as windshields for testing.

All impact tests should be recorded using high speed video. Still images must also be supplied of experimental arrangements and specimens (pre- and post-test).

Analysis

The modelling activity will use current best-practice for impact modelling against windshields. The three manned aircraft test configurations should be surveyed and FE models developed, including appropriate representation of the fuselage/supporting structure in order to accurately reflect the tests.

The FE model should be used ahead of the testing to predict the failure velocities for the UAS configurations defined in the test matrix; this will be used to inform the initial velocities used in each test configuration.

The physical testing will run in parallel with modelling activities which will allow validation/ calibration of models against the physical results; the modelling can be used to feedback into the physical testing in terms of required test impact velocity.

The WP will provide validated models which can be used with confidence in further, more complex, modelling activities.

Benefits

This test campaign will provide results that provide results that can be directly used in IEAs as well

as providing evidence for model development.

The aligned modelling activity will produce a validated predictive capability that can be used for subsequent 'blind prediction' of the threshold velocities. This can be applied for additional combinations of UAS and manned aircraft.

Precedents

The modelling activity in this WP relies on successful and accurate UAS component material characterisation carried out in WP-TM1.

This modelling activity also relies upon data obtained from WP-CA-W1; if this activity is not undertaken then it would be necessary to use best available data from the literature.

Agreement of impact cases, including component types and velocities for first tests. If completed, this may be influenced by WP-IP1, WP-IP2 and WP-TM2 (optional).

Dependents

This WP feeds into WP-CA-W3 which involves prediction of threshold velocities for different classes or examples of windshields against collision with different classes of UAS.

It also feeds directly into the Impact Effect Assessment (IEA) activities carried out in WP-IEA1.

Inputs

Windshield test specimens to be sourced.

Partial fuselage structures within which to install windshields to be sourced.

Validated UAS threat models from WP-TM1.

Validated windshield material FE impact models, material properties and technical note from WP-CA-W1.

Agreement of test matrix outlining the combination of UAS and windshields to be impacted. This may be influenced by WP-IP1 and WP-IP2 for credible UAS, aircraft and velocity combinations, and WP-TM2 which may allow some configurations to be pre-determined by comparison with existing certification tests.

Outputs

Technical notes outlining

- Test set-up and conduct

- Results from testing

- Details of modelling work

- Comparison of FE modelling with test results

Validated UAS vs laminated windshield FE models, which provide the ability to predict penetration velocity for a range of different windshield and UAS combinations.

Video footage from tests plus animations of modelling results.

Gearing / Alternatives / Scalability

There may be opportunities for EASA to gain access to existing research, which could result in significant reductions to the scope of this WP.

If fuselage sections are not available to support the windshields during test then it will be necessary to manufacture appropriate test fixtures. However, this may affect the results from the testing activity so in this case, consideration should be given to reducing the scope of the testing to reflect the reduced value of each result.

Assumptions

- Windshields and aircraft hardware shall be available at zero cost to this WP.
- Materials and construction details of the windshields can be sourced.
- Three different manned aircraft will be tested using a combination of three different UAS configurations. A total of five sets of tests will be conducted (matrix TBC).
- The activity would need to be coordinated very closely with WP-TM1, WP-CA-W1 and WP-CA-W3.

WP No. WP-CA-W3 (EASA.2016.LVP.50-WA4)		

Windshield Impact Validation - Windshield Impact Assessment

Description

This WP is primarily a modelling activity and is aimed at expanding the number of collision results using modelling methods developed and validated in the previous WPs.

This work will involve expanding the limited test and modelling results from WP-CA-W2 by considering all of the different UAS classes against each of the manned aircraft used during testing.

Results will be compiled to provide means of assessing wide range of windshield classes across different a/c types during the IEA support activity.

Benefits

Exploitation of developed models to determine the threshold penetration velocity of different MAC scenarios.

Precedents

This WP relies on the model validation from WP-CA-W1 and WP-CA-W2 for confidence in the modelling results.

This WP also relies on successful and accurate UAS component material characterisation carried out in WP-TM1.

If completed, the impact cases may be influenced by WP-IP1, WP-IP2 and WP-TM2 (optional).

Dependents

Provides information to EASA Impact Effect Assessment (IEA) at a/c component level to classify the effect (High, medium, low); carried out in WP-IEA1.

Inputs

Validated UAS threat models from WP-TM1.

Validated windshield material FE impact models, material properties and technical note from WP-CA-W1.

Validated UAS vs laminated windshield FE models from WP-CA-W2.

Agreement of the matrix of collision scenarios for evaluation; i.e. UAS / component vs windshield. This may be influenced by WP-IP1 and WP-IP2 for credible UAS, aircraft and velocity combinations, and WP-TM2 which may allow some configurations to be pre-determined by comparison with existing certification tests.

Outputs

Technical note outlining

- Collisions scenarios modelled

	-	Results from modelling, including threshold penetration velocities for all cases.
	-	Any relevant observations
Animation files of all impact simulations		

Gearing / Alternatives / Scalability

A variant of this WP would be to extend the modelling activities to include additional manned aircraft and/or new UAS configurations. This has not been included as a separate WP at this stage but is a natural follow-on.

Alternative is to rely upon validation test data for read-across, but this may not provide sufficient impact scenarios to cover all required combinations of UAS threat and manned aircraft.

This WP contributes to Recommendation 3 from the EASA Task Force Report [1].

Assumptions

- It is assumed that the model development and validation defined in WP-CA-W2 has been completed and demonstrates good correlation with test.

WP No.		
WP-CA-E1		
(EASA.2016.LVP.50-WA3)		

Engine Blade Impact Validation - Engine impact Threat Model enhancement

Description

The objective of this WP is to enhance the UAS component models developed in WP-TM1 to ensure that they are able to accurately simulate impact events against the relatively sharp leading edges of blade structures. This WP is similar to WP-TM1 but tests UAS components against 'chopping' impact modes.

Testing of UAS components:

Critical components from the four different UAS Quadcopter classes will be down-selected and up to nine impact tests performed. The tests will involve impacting the UAS components against an instrumented wedge-shaped target.

In addition to high speed video footage of each test, force-time curves will be determined and will be used to enable development of the component models.

Calibration of component theoretical models:

Data from the testing shall be processed and used to characterise homogenised material models of each component. The outcome of this work will be updated material models for each of the down-selected components, which can be used for 'chopping' mode blade analyses.

These revised component models will be demonstrated by simulating the force-time behaviour of the impact tests using FE.

Benefits

This will complement and enhance the existing component models developed in WP-TM1 to improve their response to cleaving actions associated with blade impacts.

Precedents

Preliminary testing in WP-TM1.

Dependents

This WP feeds into WP-CA-E2 which involves physical tests carried out against engine blades. It is also applicable to WP-CA-E3, WP-CA-R-T1, WP-CA-R-T2, WP-CA-R-H1 and WP-CA-R-H2.

Inputs

Validated UAS component FE models from WP-TM1.

UAS components for testing.

Agreement of wedge configuration used for impact testing.

Outputs

Technical note outlining:

- Test set-up and conduct

- Component model development and results

Updated FE models of each UAS component for use in blade impact simulations.
Gearing / Alternatives / Scalability
Alternative is to rely upon existing component materials data from WP-TM1.
Assumptions: None

WP No. WP-CA-E2 (EASA.2016.LVP.50-WA4)		

Engine Blade Impact Validation - Engine blade model development

Description

The purpose of this Work Package is to develop an understanding of the effects that ingestion of a UAS will have on the main fan stage of an example turbofan engine. It includes impact testing of UAS components against fan blades, which will be used to develop and validate an FE model. This model will then be used to predict the level of damage expected due to impacts of whole UAS against the rotating fan blades.

Note that these activities are limited to impacts against fan blades and ingestion into the bypass flow, but do not consider ingestion of UAS or components into the core. If the fan blades are shown to be tolerant of UAS impacts then further work (not in current scope) may be required to assess the more-complex core ingestion case, or impact dynamics of the whole engine.

Testing

Physical impact tests will be carried out using down-selected UAS components against blades to determine likely damage levels. In these tests the blades will be held stationary (no rotational or thrust loads) and the components will be fired at an angle to account for their relative forward and rotational velocities.

As well as recording the impacts with high-speed video and evaluating the level of damage sustained post-test, instrumentation should also be included to record deflections of the blade as this will provide useful evidence for comparison with FE modelling results.

Modelling

The initial modelling activity will include the development of FE representations of the blades and hub. The most efficient route for development of these would be to engage with engine OEMs, but if this is not possible then the geometry of a representative blade specimen will need to be surveyed and appropriate material properties researched.

The blade model should be developed, using data from the component impact tests. Once completed, this model should be expanded to include multiple blade rotating at speeds and loads appropriate to take-off conditions. Simulations should then be run to predict the response of the fan to ingestion of each of the four whole UAS Threat Models.

Benefits

Test evidence to determine the effect of UAS components impacting a fan blade.

Development of modelling approach to assess ingestion of UAS into fan blades.

Assessment of ingestion of four different UAS classes into an example turbofan engine for use in IEAs.

Precedents

The modelling activity in this WP relies on successful and accurate UAS component material characterisation carried out in WP-CA-E1 and WP-TM1 for the whole UAS threat models.

Collision likelihood and velocity data from WP-IP1 and WP-IP2 (optional).

The test activities may also be guided by output from WP-TM2 (optional).

Dependents

Provides information to EASA Impact Effect Assessment (IEA) at a/c component level to classify the effect (High, Medium, Low); carried out in WP-IEA1. The validated models also feed into WP-CA-E3.

Inputs

Fan blades and root fittings for representative engine of interest e.g. large airliner class.

Design data on the engine of interest. This should include fan blade geometry, materials, and engine operating speeds and loads.

Validated UAS threat models from WP-TM1.

Outputs

Technical note outlining:

- Test set-up and conduct
- Test results
- Model development and validation
- Predictions of fan damage for ingestion of each of the four classes of UAS

Validated UAS vs engine blade FE models

Video footage of tests and animations from FE modelling studies.

Gearing / Alternatives / Scalability

If test specimens or basic design data cannot be obtained then alternative approaches can be considered separately.

Output from the Particular Risks study may provide data to support the most appropriate selection of components for impact testing.

Assumptions

- Engine fan blades and hub fitting (one design only) to be supplied free of charge.
- Fan blades are of traditional metallic design rather than new composite examples. Additional effort and fundamental testing would be required for composite blades.
- Sufficient design data can be sourced from OEMs/suppliers to allow example blades to be modelled. Alternative options exist if this is not possible.
- The current illustration assumes up to four impact tests against fan blades.
- Activities within this WP are limited to considering failure of the main fan. The effect of debris on downstream systems is not part of the planned activity and should be considered to be an ongoing risk. The significance of this risk may be best understood through discussions with engine OEMs.
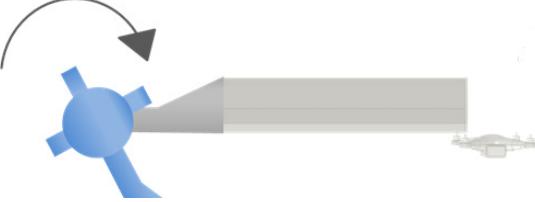
| **WP No**.

WP-CA-E3

(EASA.2016.LVP.50-WA4) | | |

| **Engine Blade Impact Validation - Engine ingestion modelling** |

Description

This Work Package builds upon WP-CA-E2 but expands the scope to include an additional fan design e.g. for smaller/larger engine.

The activity doesn't include any additional testing but exploits the modelling methods developed in WP-CA-E2 to predict the response of the additional fan design to ingestion of each of the four different classes of UAS.

This example WP assumes one new blade configuration, though economies of scale may be achieved if more than one additional design were to be considered concurrently.

The outcome of this WP will be vulnerability assessments for the selected fan design against each of the four classes of UAS.

Benefits

Evidence for IEAs on the vulnerability of engine fans against whole UAS of each mass class.

Precedents

The modelling activity in this WP relies on Threat Models generated in WP-TM1 and ideally, enhancements to the material characterisation carried out in WP-CA-E1.

It also relies upon the FE modelling methods developed in WP-CA-E2.

Collision likelihood and velocity data from WP-IP1 and WP-IP2 (optional).

The test activities may also be guided by output from WP-TM2 (optional).

Dependents

Provides information to EASA Impact Effect Assessment (IEA) at a/c component level to classify the effect (High, Medium, Low); carried out in WP-IEA1

Inputs

Design data on the blades/engines of interest. This should include geometry, materials, and engine operating speeds and loads.

Validated UAS component FE models from WP-TM1.

Validated UAS vs engine blade FE models from WP-CA-E2.

Data to define aircraft collision speeds and severities from WP-IP1, WP-IP2 and WP-TM2.

Outputs

Technical note outlining:

-   Predictions of fan damage for ingestion of each of the four classes of UAS

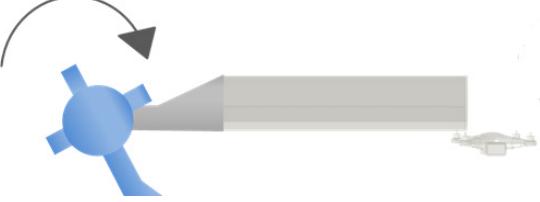Animations from FE modelling studies.

Gearing / Alternatives / Scalability

The alternative would be to rely upon the single point test data generated in WP-CA-E2 to guide IEAs.

Assumptions

- Fan blades are or traditional metallic design rather than new composite examples. Additional effort and fundamental testing would be required for composite blades.
- Engine design data required to undertake impact assessments can be sourced from OEMs/suppliers. This should include geometry data (in agreed CAD format), materials data and engine operating speeds.
- Activities within this WP are limited to considering failure of the main fan. The effect of debris on downstream systems is not part of the planned activity and should be considered to be an ongoing risk. The significance of this risk may be best understood through discussions with engine OEMs.

WP No. WP-CA-R-T1 (EASA.2016.LVP.50-WA3)		

Tail Rotor Impact Validation - Tail Rotor model validation

Description

The objective of this WP is to undertake impact testing against an example tail rotor blade design in order to generate data that can be used to: develop and validate FE modelling methods, and; enable initial IEAs to be made for tail rotor impacts.

Testing

Physical impact testing will be conducted using UAS components against a single design of tail rotor blade in order to determining damage levels.

Up to four impacts will be undertaken to separate blade of the same design. These will use down-selected components from the four UAS Quadcopter configurations, fired at speeds appropriate to the rotational speed of the rotor and impact location. Nominally, the impact location will be near the blade tip, as this is assumed to be the most vulnerable region.

Transient structural deflections of the rotor blades should be recorded.

All impact tests should be recorded using high speed video. Still images must also be supplied of experimental arrangements and specimens (pre- and post-test).

Modelling

The modelling activity will use current best-practice for impact modelling against metallic/composite/honeycomb structures.

FE models of the test specimens should be developed and data from the test results used to develop them further. However, note that calibration of input values such as material strengths should be maintained within credible values.

Comparisons should be made between the final FE results and test evidence. Assuming that an acceptable correlation is achieved, the models will be re-run considering the effects of rotational forces on the blades and impacts against the whole UAS Threat Models.

Benefits

Validation of modelling, and confidence in use of the modelling, for subsequent prediction of the tail rotor damage levels.

Collision test data and modelling data to support IEAs for the example blade design.

Precedents

The modelling activity in this WP relies on successful and accurate UAS component material characterisation carried out in WP-TM1.

Collision likelihood and velocity data from WP-IP1 and WP-IP2 (optional).

The test activities may also be guided by output from WP-TM2 (optional).

Dependents

This WP feeds into WP-CA-R-T2 which involves prediction of damage levels for different CS-classes of tail rotor against collision with different classes of UAS.

Provides information to EASA IEAs at a/c component level to classify the effect (High, Medium, Low); carried out in WP-IEA1.

Inputs

Tail rotor blades (assumed to be supplied at zero cost to this WP).

Design data for blades including material types and construction. Also either CAD data or access to blades for structural survey.

Validated UAS threat models from WP-TM1.

Validated enhanced UAS component models from WP-CA-E1, if available (optional).

Optional data to define collision speeds and severities from WP-IP1, WP-IP2 and WP-TM2. Note that the impact speeds are likely to be dominated by the tip speeds of the rotors rather than relative velocities of the aircraft.

Outputs

Technical note outlining:

- Blade design and impact cases

- Experimental arrangement and test results

- Model results compared to test cases

- Model results for whole UAS into rotating blades

Validated UAS vs tail rotor blade FE models; ability to predict amount of damage in tail rotor blades under consideration.

Video footage of tests and animations of FE modelling results.

Gearing / Alternatives / Scalability

Alternative is to rely upon existing modelling methods without further validation.

The testing activity could be extended to include detailed NDE and forensic evaluation of the impacted test specimens in order to determine extent and types of damage sustained. However, this isn't included within the current WP.

Assumptions

- Sufficient design data can be sourced from OEMs/suppliers to allow efficient progress of impact modelling.
- Four-off tail rotors are available for destructive testing, free of charge.
- All specimens provided will be of the same design.

WP No. WP-CA-R-T2 (EASA.2016.LVP.50-WA4)		

Tail Rotor Impact Validation - Tail Rotor Impact Assessment

Description

This WP is primarily a modelling activity and is intended to utilise the validation modelling methods from WP-CA-R-T1 to undertake additional collision assessments. Provisionally, two different blade designs are assumed, each of which is to be assessed against four UAS configurations.

This work will involve a survey of up to two example aircraft tail rotors that fit the CS-classes of interest.

Model generation and parametric analysis of UAS impacts (four mass classes) against two tail rotor targets, two strike positions (hence two impact velocities) to determine damage levels.

Compilation of results to provide means of assessing wide range of tail rotor classes across different a/c types.

Benefits

Provides a relatively inexpensive method of determining the damage levels of different MAC scenarios against tail rotors.

Precedents

This WP relies on the model validation from WP-CA-R-T1 for confidence in the predictions; alternatively existing impact modelling methods without validation could be utilised (but this is not recommended).

It would benefit from enhanced component impact data from WP-CA-E1 (optional).

Collision likelihood and velocity data from WP-IP1 and WP-IP2 (optional).

The test activities may also be guided by output from WP-TM2 (optional).

Dependents

Provides information to EASA Impact Effect Assessment (IEA) at a/c component level to classify the effect (High, medium, low); carried out in WP-IEA1.

Inputs

Geometry, materials, construction data and operating speeds for two tail rotors.

Agreement of the matrix of collision scenarios for evaluation; i.e. UAS / component vs tail rotors at different locations.

Validated UAS threat models from WP-TM1.

Validated enhanced UAS component models from WP-CA-E1, if available (optional).

Validated UAS vs tail rotor blade FE models from WP-CA-R-T1.

Optional data to define collision speeds and severities from WP-IP1, WP-IP2 and WP-TM2. Note that the impact speeds are likely to be dominated by the tip speeds of the rotors rather than relative velocities of the aircraft.

Outputs

Technical note including:

- MAC scenarios assessed
- Results from analyses

Animations of the impact analyses.

Gearing / Alternatives / Scalability

This WP contributes to Recommendation 3 from the EASA Task Force Report [1].

Assumptions

- Appropriate design details can be sourced from OEMs/suppliers for the down-selected blades of interest.

| **WP No**.

WP-CA-R-H1

(EASA.2016.LVP.50-WA3)		

Main Rotor Hub Impact Validation – Main Rotor Hub model validation

Description

The objective of this WP is to undertake impact testing against an example rotor hub design in order to generate data that can be used to: develop and validate FE modelling methods, and; enable initial IEAs to be made for rotor hub impacts.

Testing

Physical impact testing will be conducted using UAS components against a main rotor hub, containing swash plate, pitch and teeter hinges, and pitch linkages, to aid in determining damage levels.

Impacts will be carried out using UAS components rather than whole systems because the areas that are perceived to be most vulnerable (likely to be the linkages, or hinge to the linkage) are relatively small. The testing will be carried out at velocities relating to the possible range of impact velocities, providing valuable insight into the vulnerability of these mechanisms and validation "points" for additional modelling work. Up to four impact tests will be carried out.

All impact tests should be recorded using high speed video. Still images must also be supplied of experimental arrangements and specimens (pre- and post-test).

Modelling

The modelling activity will use current best-practice for impact modelling against such metallic components and structures. The outcome will be test data that gives strong evidence for the vulnerability of the tested hub design and validated FE models which can be used with confidence in further modelling activities.

Benefits

Validation of modelling, and confidence in use of the modelling, for subsequent prediction of the damage levels for the main rotor hub of various a/c.

Precedents

The modelling activity in this WP relies on successful and accurate UAS component material characterisation carried out in WP-TM1 and would also benefit from data from WP-CA-E1.

Collision likelihood and velocity data from WP-IP1 and WP-IP2 (optional).

The test activities may also be guided by output from WP-TM2 (optional).

Dependents

This WP feeds into WP-CA-R-H2 which involves prediction of damage levels for different CS-classes of main rotor hubs against collision with different classes of UAS. It also provides data to support WP-IEA1.

Inputs

Provision of agreed design of main rotor hubs.

Materials data for components and geometry of main rotor assembly.

Agreement of impact cases for test (guided byWP-IP1 , WP-IP2 and WP-TM2 (optional).

Validated UAS threat models from WP-TM1.

Validated enhanced UAS component models from WP-CA-E1, if available (optional).

Outputs

Technical note including:

- Details of set-up, test conduct and results

- Details of modelling work and validation

 Validated UAS vs main rotor hub FE models.

Gearing / Alternatives / Scalability

Alternative is to rely upon existing modelling methods without further validation to assess the threat to hub designs

Assumptions

- All rotor hub hardware to be provided, free of charge.
- The supplied hub will be detached from the fuselage to aid handling and testing. The self-contained assembly will include a simple interface that can be used to secure the specimen for test.
- Additional hub components will be provided to replace items damaged during test.
- Design data for the hubs, including materials, to be provided.
- Only one hub assembly to be tested.

WP No. WP-CA-R-H2 (EASA.2016.LVP.50-WA4)	

Main Rotor Hub Impact Validation - Main Rotor Hub Impact Assessment

Description
This WP is primarily a modelling activity. The work will involve a survey of example aircraft main rotor hubs that fit the CS-classes of interest, down-selected to two. Model generation and parametric analysis of UAS impacts (four mass classes) against two main rotor hubs, possibility to impact the same hub a number of times; different strike positions; different impact velocities, to determine damage levels. Compilation of results to provide means of assessing wide range of main rotor hub classes across different a/c types.

Benefits
Provides an efficient method of determining the damage levels of different MAC scenarios.

Precedents
This WP relies on the model validation from WP-TM1 and WP-CA-R-H1 for confidence in the predictions; alternatively existing impact modelling methods without validation could be utilised (but this is not recommended). It would benefit from enhanced UAS component data from WP-CA-E1 (optional). Collision likelihood and velocity data from WP-IP1 and WP-IP2 (optional). The test activities may also be guided by output from WP-TM2 (optional).

Dependents
Provides information to EASA Impact Effect Assessment (IEA) at a/c component level to classify the effect (High, medium, low); carried out in WP-IEA1.

Inputs
Materials data for components and geometry of two main rotor hub assemblies (OEM input desirable). Agreement of matrix of collision scenarios for evaluation; i.e. UAS / component vs main rotor hubs at different locations/velocities (guided by WP-IP1 , WP-IP2 and WP-TM2 (optional). Validated UAS threat models from WP-TM1. Validated enhanced UAS component models from WP-CA-E1, if available (optional). Validated UAS vs main rotor hub FE models from WP-CA-R-H1.

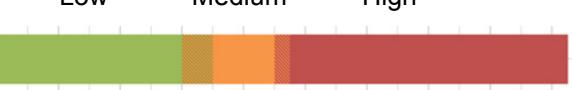| **Outputs** |
|---|
| Technical note including:

- MAC scenarios assessed |

- Results from analyses

Gearing / Alternatives / Scalability

Alternative is to rely upon validation test data for read-across, but damage threshold velocities prediction would be a risk.

This WP contributes to Recommendation 3 from the EASA Task Force Report [1].

Assumptions

- Appropriate design data can be sourced from OEMs/suppliers/operators to enable modelling work to be undertaken.

WP No. WP-IEA1 (EASA.2016.LVP.50-WA4)		Low Medium High

EASA Impact Effect Assessment (IEA) Process

Description

This WP includes the organisation of data generated from feature-based research activities (i.e. panels, windshields, engine, rotors) into a more user-friendly repository or tool that can be interrogated when making IEAs.

This WP also includes support to EASA for the determination of IEAs as part of the Impact & Hazard Effect Assessment process.

Benefits

Provides a database of the effect that different classes of UAS threats has on specified components of different classes of a/c.

Precedents

Requires outputs from WP-TM2, WP-CA-P-M/C/S2, WP-CA-P-M/C/S3, WP-CA-W2, WP-CA-W3, WP-CA-E2, WP-CA-E3, WP-CA-R-T1, WP-CA-R-T2, WP-CA-R-H1 and WP-CA-R-H2 (Output from each feature type enables IEA of that feature).

Also, outputs from WP-IP1 and WP-IP2 would provide improved data on impact velocities and output from WP-TM2 may enable some scenarios to be assessed by comparison with existing certification results.

Dependents

WP-HEC1.

Inputs

Details of collision scenarios for evaluation, including UAS threat, target geometry & materials, and impact speeds & angles. If available, this may be influenced by WP-IP1 and WP-IP2 for credible UAS, aircraft and velocity combinations.

Data from each WP:

- Predictive and test results from WP-CA-P-M/C/S2 and WP-CA-P-M/C/S3 for penetration thresholds and damage levels for Panel Feature Assessments: metallic (M), monolithic composite (C) and sandwich composite (S).

- Predictive and test results from WP-CA-W2 and WP-CA-W3 for penetration thresholds and damage levels for Windshield Impact Assessment.

- Predictive and test damage assessment results WP-CA-E2 and WP-CA-E3 of engine fan blades, including blade-off predictions.

- Predictive and test results for penetration thresholds and damage levels from WP-CA-R-T1 and WP-CA-R-T2 for Tail Rotor Impact Assessment.

- Predictive and test results for penetration thresholds and damage levels from WP-CA-R-H1 and WP-CA-R-H2 for Main Rotor Hub Impact Assessment.

If available, WP-TM2 may allow some configurations to be pre-determined by comparison with

existing certification tests.

Any available in-service collision data and damage assessments.

Outputs

Database defining the Impact Effect Assessment (IEA) that different classes of UAS threats has on specified components of different classes of a/c; this will rely heavily on the EASA IEA definitions shown in Appendix VIII of [1].

Gearing / Alternatives / Scalability

WP No.		
WP-HEC1		
(EASA.2016.LVP.50-WA5)		

EASA Hazard Effect Classification (HEC)

Description
The purpose of this WP is to support EASA in determining the final effect at aircraft level, based on the predictive work of UAS threats against specified components and the resulting IEA.

The Hazard Effect Classification (HEC) at a/c level will be made utilising the EASA HEC definitions shown in Appendix VIII of [1]. Here a severity level (1-5) will be applied to the following:

- Effect on a/c;
- Effect on occupants (ex. Flight Crew);
- Effect on Flight Crew;
- Effect on Operations.

This task will not include any experimental or modelling activities, but will be an analytical and deductive task.

Benefits
Provides a database in terms of the hazard effect that different classes of UAS threats has on different classes of a/c.

Precedents
Requires outputs from WP-IEA1 and would benefit from impact probability assessments from WP-IP1 and WP-IP2.

Dependents: EASA safety management activities

Inputs
Database defining the Impact Effect Assessment (IEA) that different classes of UAS threats has on specified components of different classes of a/c, from WP-IEA1.

Findings from WP-IP1 and WP-IP2, to aid assessments of the likelihood of impacts occurring.

This WP should be carried out by a working group which include aircraft manufacturers, operators, and EASA.

Outputs
Database defining the Hazard Effect Classification (HEC) that different classes of UAS threats has on different classes of a/c.

Gearing / Alternatives / Scalability

Assumptions

- Agreement to be reached with EASA for the level of input required and number of different assessments to complete.

Initial Distribution List

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