Predicting and mitigating failures on the flight deck: An aircraft engine bird strike scenario

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Abstract

Commercial aircraft engine damage as a consequence of foreign object debris (FOD) during flight is frequently caused by birds. One approach to minimising the disruption caused by this type of engine damage is to provide commercial flight crew with accurate information relating to the continuing operational status of the aircraft's engines. Before designing avionic systems to achieve this however, understanding of current procedures is needed. Hierarchical Task Analysis (HTA) and Systematic Human Error Reduction and Prediction Approach (SHERPA) were used to identify potential failures that commercial flight crew may make when managing an engine bird strike. Workshops with commercial pilots generated insights into current practice and a commercial pilot SME reviewed outputs for accuracy. Over 200 potential failures were identified, most commonly related to communication. Remedial measures, considering future avionic systems, have been proposed to mitigate identified failures. This analysis provides a starting point for future design concepts for assisting commercial flight crew in dealing with engine malfunction due to FOD strikes.

Key Words: Aviation; HTA; SHERPA; failure analysis; bird strike

Practitioner Summary

Hierarchical Task Analysis was conducted to show all tasks involved in dealing with an in-flight aircraft engine bird strike. Systematic Human Error Reduction and Prediction Approach analysis was performed and over 200 possible failures were identified when managing this event. Remedial measures are proposed to help mitigate possible failures.

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According to Mao et al. (2008), more than 90% of foreign object debris (FOD) damages to aircraft engines can be attributed to avian creatures. This makes engine bird strikes a leading safety concern within the aviation industry (Hedayati et al., 2014). Bird strike events are not rare (Nicholson & Reed, 2011), in fact, engine bird strikes occurred as soon as aircraft took to the skies, with the first being recorded by Wilbur Wright in 1905 (Guida et al., 2013). Engine bird strikes can often be benign, but they do also have the potential to cause significant disruption and flight safety ramifications (Nicholson & Reed, 2011; Guida et al., 2013). Dolbeer et al. (2019) cite bird strikes as being responsible for more than 287 fatalities and the loss of 263 aircraft in the aviation industry over the last thirty years.

Whilst safety is, of course, the main priority when considering engine FOD as a consequence of bird strikes, there are also significant economic costs associated with the damage sustained in such events. Two main approaches have been adopted to try and reduce the costs associated with injury, fatality and loss of aircraft that result from wildlife collision. First, there are bird strike prevention methods that aim to reduce the probability of incidents occurring, either by culling bird populations in airport vicinities (Kelly & Allan, 2006) or technological solutions to discourage birds from approaching such as the use of pulsed landing lights, infrasound, and fuselage colour schemes (MacKinnon et al., 2001; Martin, 2011). Second, there are aircraft certification programmes that aim to ensure the integrity of the airframe (e.g., CS-25.631, European Aviation Safety Agency, 2019) and certification programmes for the engines (e.g., Airworthiness Code CS-E 800, European Aviation Safety Agency, 2018) following a high velocity impact. A third potential approach, which is currently underutilised, is to provide flight crew with greater support when handling such events via flight deck displays and avionics. Supporting flight crews with well-designed interfaces has the potential to enhance their decision making, potentially helping to ameliorate the situation and improve the outcome of such events.

Commercial Airline Pilot Response to an Engine Bird Strike

One of the most public examples of an engine bird strike is US Airways Flight 1549 that was forced to land on the Hudson River following dual engine bird strikes which caused a loss of thrust to both engines on January 15, 2009 (Marra et al., 2009). However, within the National Transportation Safety Board (NTSB; 2010) accident report, one of the contributing factors to the fuselage damage was *"the captain's resulting difficulty maintaining his intended airspeed on final approach due to the task saturation resulting from the emergency situation"* (p. xv). The documentation associated with this investigation provides in-depth records of post event flight crew interviews that provide considerable insight into the startle and surprise effects during this incident.

Startle occurs when operators are exposed to a sudden, intense stimulus (Bradley et al., 1993; Martin et al., 2015). This causes an involuntary physiological reflex in which the body is prepared for the fight-flight response (Koch, 1999; Grillon & Baas, 2003). In the context of aviation, startle may induce pilot disorientation, task interruption and brief confusion (Nakagawara et al., 2004). Surprise, in contrast, results from a disparity between an individual's expectations and what is actually perceived (Hortsmann, 2006). Unlike startle, surprise can occur following the presence or absence of a stimulus (Rivera et al., 2014; Bürki-Cohen, 2010). The physiological and psychological effects of surprise are largely comparable to that of startle, including increased heart rate, increased blood pressure, confusion, loss of situation awareness and the inability to remember the current operating procedures (Rivera et al., 2014). The European Union Aviation Safety Agency (EASA; 2015) recognises that pilot performance may be impaired by startle and surprise resulting in inappropriate responses. This means that well-learned procedures and skills could be momentarily forgotten and instead replaced by pilots freezing or overreacting at the controls (Koch, 1999; Rivera et al., 2014).

There is of course variation in the potential effects of bird strike can have on both the aircraft and the flight crew. Implementing a key recommendation from the NTSB accident report in relation to recent engine bird strike events, there has been a call for the Federal Aviation Administration (FAA) to work more closely with *"the military, manufacturers, and National Aeronautics Space Administration to complete the development of a technology capable of informing pilots about the continuing operational status of an engine. (A-10-62)"* (NTSB, 2010; p.124). With this in mind, and as with any novel technology entering the 6ommercial flight deck, it is important to understand and, as far as possible, pre-empt the types of failure that could occur when pilots are trying to manage engine damage following a significant bird strike event. The present research aims to inform aircraft manufactures of the types of potential errors commercial pilots could make as a consequence of aircraft engine damage and provide design recommendations for novel technology that could facilitate the continued operational status of the engine in the event of a bird strike. An error analysis is conducted to identify potential failures, as well as providing mitigation strategies to minimise them.

Error Analysis

Human Error Identification (HEI) techniques have emerged as a useful way to identify and predict the types of error that may occur between human-computer interactions (Baber & Stanton, 1996; Kirwan, 1998). HEI techniques can then be used to formulate remedies to overcome these errors and help inform design principles (Baber & Stanton, 1994;

Stanton et al., 2013; Parnell et al., 2019). Two methods are used here in combination. Firstly, Hierarchical Task Analysis (HTA; Annett et al., 1971) is used to decompose the task into its simplest operations. HTA is a powerful technique because it forms the starting point for many other complex HEI methodologies (Parnell et al., 2019). HTA representations are essentially comprised of a hierarchy of goals. These goals are broken down into operations. Each operation is then broken down into plans to provide an indication of task sequence and flow (Annett et al., 1971). In this paper, HTA will be used to determine all of the required steps required to manage an engine bird strike from the perspective of the flight crew. This representation will then be used to inform a Systematic Human Error Reduction and Prediction Approach (SHERPA; Embrey, 1986) analysis. SHERPA works on the assumption that errors can be predicted when reviewing the tasks to be performed (Baber & Stanton, 1996; Stanton & Stevenage, 1998; Stanton & Baber, 2002). It is now understood that when applying such methods it is the failures of the system that need to be identified, not the individual errors which can detract from the main cause of adverse events (Read et al, 2021). Thus this investigation will review failures, not errors. By reviewing a HTA of a bird strike scenario it is possible to predict the types of failures that may occur, classify their likelihood and criticality, and generate remedial measures in which these failures may be ameliorated. With the objective of being able to provide a list of recommendations to be considered in the design of new flight deck technologies that aim to support and inform the commercial pilots about the *"continuing operational status of an engine"* (NTSB, 2010, p. 124), the decision to combine HTA and SHERPA was reached.

Method

Scenario

When performing failure analysis, it is necessary to review a hypothetical scenario in which a failure could occur. In order to constrain the analysis, a hypothetical scenario of an engine bird strike event was used. In this scenario, a twin-engine aircraft is envisaged during its initial climb phase. At approximately 600 feet, a flock of birds strike both engines, significant enough to cause malfunction indicators to be triggered. In order to understand how this may impact upon the behaviour of the flight crew, workshops were held with commercial airline pilots to understand their approach to an engine bird strike event. For the purpose of the analysis, standardisation of the aircraft model was employed with the Boeing flight deck design being used with two pilots required to fly the aircraft. Pilots and SMEs were familiar with this cockpit architecture. Ethical acceptance was granted from the research institute (Ethical Research Governance Office, reference 46045).

Participants

Seven commercial airline pilots (6 males, 1 female), aged between 28 and 63 (M = 37.7, SD = 12.6) took part in three separate workshops, and had held their licences for an average of 14.6 years (SD = 13.9). The least experienced participant had held their licence for 4 years, while the most experienced participant had held theirs for 44 years. Thus, the number of commercial hours logged ranged from 2500 to 26000 (mean = 8142.9, SD = 8124.4).

Workshop Procedure

Within each workshop, the airline pilots were asked to discuss how they would approach a dual engine bird strike, in terms of determining criticality and appropriate response, for the hypothetical scenario generated. Participants were asked to imagine they were in the scenario stated above and then detail their response, including the type of information they would require and the actions they would take. Any confounding factors that would impact on their actions were also discussed. Discussions were audio recorded and later transcribed. Transcriptions from the workshops were used to develop the HTA.

Hierarchical Task Analysis

Using the information gained from the pilot workshops, the HTA was developed by a team of Human Factors practitioners with assistance from a Subject Matter Expert (SME) who was an experienced commercial airline pilot with over ten years' flight experience. The Human Factors practitioners first compiled the HTA and subsequently validated it with the SME to ensure accuracy. HTA methodology outlined in Huddlestone and Stanton (2016) was followed. The HTA identified all of the tasks conducted during the scenario and the plans that facilitate subsequent tasks. Tasks are shown in square boxes; plans are shown in oval boxes. The tasks that are connected to each other horizontally occur sequentially. For tasks that require a plan to determine the sequencing of tasks, the plan is noted in an oval and then linked to the relevant tasks (Huddlestone & Stanton, 2016). Checklists from publically available Quick Reference Handbooks (QRH) containing all of the procedures to be used in abnormal and emergency conditions were also used to populate plans to ensure accuracy. As the scenario dictated engine damage as a consequence of a bird strike, the severe engine damage checklist was deemed appropriate for inclusion in the HTA by the SME. The outcome of this HTA is a complete breakdown of the scenario into all tasks and decisions that need to be made when responding to the bird strike event.

Systematic Human Error Reduction and Prediction Approach

Once the HTA had been constructed, failure prediction analysis could be conducted. This involved using the SHERPA taxonomy (Embrey, 1986; Stanton & Stevenage, 1998) against each of the bottom level tasks within the hierarchy to predict the type of failures that could occur across each of the tasks. The SHERPA methodology classifies the failures into a comprehensive taxonomy including: action, checking, retrieval, communication or selection failures (Embrey, 1986; Stanton & Stevenage, 1998). Within each of these failure modes, there are number of possible failure codes documenting specific failure types, for example within the checking mode, specific failure codes include check omitted and check mistimed. The likelihood and criticality of each failure can then be individually assessed (Stanton et al., 2013). Low likelihood was classified as occurring never or rarely; medium likelihood was classified as happening occasionally or had happened before and; finally, high likelihood was classified as occurring frequently. Low criticality, in contrast, was classified as posing no danger to life or injury; medium criticality was classified as posing a risk of injury and; high criticality was classified as posing a risk to life (Stanton et al., 2013). These classifications have been widely applied in previous literature using the SHERPA methodology (e.g. Stanton & Stevenage, 1998; Stanton & Barber, 2002; Stanton et al., 2002; Parnell et al., 2019). The Human Factors practitioners conducted the SHERPA which was subsequently reviewed by the same commercial airline pilot SME who validated the HTA. The SME was integral in the classification of the failure likelihood and criticality. Finally, each failure was discussed in light of any possible remedial measures that could be implemented to either reduce the likelihood of the failure from occurring, or reduce the impact of such an failure. These remedial measures aimed to respond to the NTSB (2010) request for aircraft manufacturers to "*develop technology capable of informing pilots about the continuing operational status of an engine"* as well as assist in pilots' response to engine malfunction events such as bird strikes.

Results & Discussion

Hierarchical Task Analysis

The HTA was developed in an iterative manner and was based on the following assumptions: that the aircraft was being operated under current dual-crew configuration; pilots were adequately trained and airworthy; that appropriate landing facilities were available and; a safe landing was possible. Caution is warranted that in the event that any of these assumptions are violated, the HTA will no longer be valid. A snapshot of the HTA is presented in Figure 1 and shows the overall goal (Goal 0: "Monitoring and responding to threats on take-off") and the high level operations that reside beneath it.

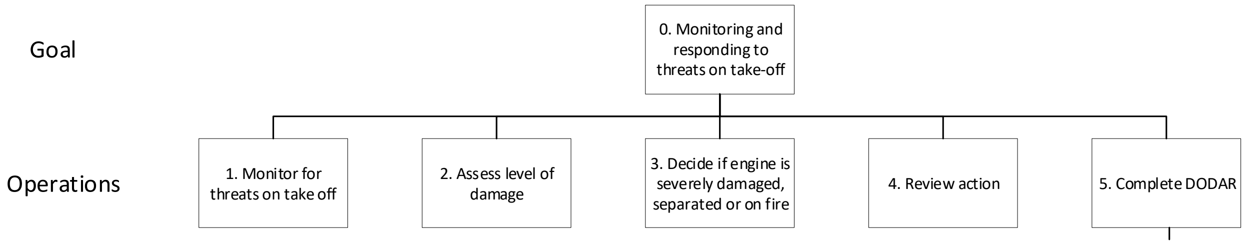

Figure 1. Snapshot of the HTA showing the overarching goal and operations involved in managing an engine bird strike event.

In order to achieve Goal 0, it was recognised that airline pilots need to make a dynamic assessment of what has happened, identify the location of any potential engine damage and assess the criticality. Thus, a total of five core sub-goals (or operations) were identified;

1. Monitor for threats on take-off: Within this sub-goal, the flight crew may notice a flock of birds in close proximity to the aircraft upon take off. Depending upon the size and type of aircraft, pilots may hear the impact of birds striking the engines. If autopilot is not already engaged, the Pilot Flying (PF) would activate it if available.
2. Assess level of damage: In order to assess the severity of the bird strike, flight deck crew would begin monitoring engine status displays to check for any abnormalities in temperature, pressure and vibration levels. Crew must also determine if any engines are severely damaged, separated or on fire. They will look to the EICAS or ECAM displays to determine if significant damage has occurred. Any abnormalities or

warnings must be verbalised by the Pilot Monitoring (PM) and verbally confirmed by the PF.

3. Follow procedure: The procedure that is followed will depend upon the outcome of the assessment made in sub-goal 2. If the engine is severely damaged, separated or on fire, flight crews will action memory items to secure the engine and then declare a mayday call to air traffic control (Procedure A). However, if the engine is not severely damaged, separated or on fire, a mayday will still be called in to air traffic control. Thus, rather than taking immediate action, pilots will choose to proceed to a pre-determined minimum safe altitude (MSA). At MSA, pilots will refer to the QRH to determine what actions are required (Procedure B). These procedures are subtly different and therefore are treated separately throughout the remainder of this analysis.
4. Review action: Following completion of an appropriate procedure, the flight crew will then review their actions. This will consist of checking and monitoring the engine parameters displayed on the engine page and also the status of EICAS or ECAM systems. Further, the crew will need to check that the aircraft is maintaining the desired speed and altitude by looking at the primary flight display.
5. Complete DODAR: When time allows, the flight crew will utilize decision making strategies, such as DODAR (Diagnose, Options, Decision, Assign task, Review; Walters, 2002) or FORDEC (Facts, Options, Risks, Decide, Execute, Check; Hörmann, 1995) to organise their thoughts and reassess what has happened / is going to happen. Within the HTA, a decision was made to adopt DODAR because all seven participants involved in the workshops said that this was the strategy they had been taught. The HTA differentiates between the PF and PM roles here as each have different responsibilities. Given the complexity of the situation, we have chosen to

end the HTA for the PF as Task 5.3.1.1.a. ‘Maintain control of flight’. Realistically, an entirely new HTA could be performed to account for such a task but this was deemed beyond scope of the current analysis. Instead, we focus on the PM and the operational tasks that must be completed. For the complete HTA, please see the online supplementary material.

Systematic Human Error Reduction and Prediction Approach

Bottom level tasks from the HTA were individually assessed to determine where failures may occur as well as their likelihood and criticality, before identifying possible remedial strategies to mitigate the failures. Given that the procedure that is followed will be based upon the outcome of the assessment made in sub-goal 2 (‘Assess level of engine damage’), the results of the SHERPA have been divided into Procedure A, considering severe engine damage and Procedure B, considering non-severe engine damage. Table 1 presents the frequency of failure for each failure sub-category.

Table 1. Frequency of failure

Failure categories	**Failure sub-categories**	**Failures (n)**	
		Procedure A	**Procedure B**
Action	Operation mistimed (A2)	4	4
	Operation too much/too little (A4)	1	1
	Right operation on wrong object (A6)	8	8
	Wrong operation on the right object (A7)	0	0
	Action omitted (A8)	45	49
	Total Action Failures	***58***	***62***
Checking	Check omitted (C1)	20	20

	Right check on the wrong object (C3)	7	7
	Total Checking Failures	***27***	***27***
Selection	Selection omitted (S1)	0	1
	Wrong selection made (S2)	6	9
	Total Selection Failures	***6***	***10***
Communication	Information not communicated (I1)	32	31
	Wrong information communicated (I2)	25	25
	Information communication incomplete (I3)	20	20
	Total Communication Failures	***77***	***76***
Retrieval	Information not obtained (R1)	21	21
	Wrong information obtained (R2)	14	15
	Information retrieval not complete (R3)	2	2
	Total Retrieval Failures	***37***	***38***
Total failures		**205**	**213**

Whilst there appears to be more of an increase in the overall possibility of failure for Procedure B, this is attributable to the subtle differences in the operational tasks that are required to be completed in comparison to Procedure A. With non-severe engine damage, pilots have more options available to them to maintain flight, whereas after sustaining severe engine damage the pilots need to land the aircraft as quickly and as safely as possible. Regardless of damage, the most common potential failure type identified was 'Communication'. Communication failures represent tasks which require communication between the PF and the PM, and between the flight deck and other agents, e.g. Air Traffic Control and Cabin Crew. This is unsurprising as communication is critical in ensuring that both pilots have the same understanding of the developing situation . Within this context, startle and surprise may disrupt coordination between the PF and PM (Billings & Cheaney, 1981). The large number of failures highlighting the potential for missed communication and mismatched situation awareness between the flight crew as identified in the SHERPA, supports this notion.

When looking at specific failure types, the most common failure code was action failure (A8): Operation omitted. Examples include failing to read engine gauges (temperature, pressure, vibration) which in turn can disrupt flight crews' levels of situation awareness; failing to press the Push-To-Talk button meaning that the flight crew are not able to communicate with Air Traffic Control; and failing to carry out required steps from the QRH checklist. This supports the claims by Koch, (1999) and Rivera et al., (2014) that unexpected events such as bird strikes can disrupt well-learned procedures and skills and prevent pilots from taken the required actions to maintain safe flight, further highlighting the potential of flight operations as a consequence of startle and surprise.

Failure Classification

The total frequency of failures as classified by their likelihood and criticality for both Procedure A, severe engine damage, and Procedure B, non-severe engine damage, are shown in Table 2a and 2b respectively. Failures that are classified as low criticality and low likelihood are often ignored in favour of focusing on those that include an element of criticality (Parnell et al., 2019). Within this SHERPA, the most common failure rating, regardless of procedure followed, was low likelihood, medium criticality (see Table 3 for examples). However, there were also numerous examples of potential failures rated as low likelihood, high criticality (see Table 3 for examples). Medium and high criticality failure were the focus of the development of possible remedial design measures aimed to mitigate the occurrence of such failures.

Table 2a. The frequency of failure likelihood and criticality ratings for Procedure A, severe engine damage.

Criticality	**Likelihood**		
	Low	**Medium**	**High**
Low	23	1	0
Medium	149	0	0
High	32	0	0

Table 2b. The frequency of failure likelihood and criticality ratings for Procedure B, non-severe engine damage.

Criticality	**Likelihood**		
	Low	**Medium**	**High**
Low	24	1	0
Medium	160	0	0
High	28	0	0

Table 3. Examples of key failures identified within the SHERPA as categorised by likelihood and criticality.

		Likelihood		
		Low	**Medium**	**High**
Criticality	**Low**	N/A	• Failure to check external environment on take-off	0
	Medium	• Failure to check for engine fluctuations • Failure to check for any missing parameters • Failure to verbalise any abnormalities • Failure to retrieve and follow the correct procedure within the QRH • Failure to communicate effectively to verify the situation • Failure to agree on appropriate action • Failure to use appropriate controls • Failure to calculate performance calculations	0	0
	High	• Failure to check EICAS/ECAM messages • Failure to check speed • Failure to check altitude • Failure to communicate with Air Traffic Control • Failure to produce accurate performance calculations • Load inaccurate performance calculations in the Flight Management Computer	0	0

Development of remedial measures

With the incident of a bird strike often being unexpected and leading to unpredictable levels of aircraft engine damage and consequences to the flight, improving the interface between the pilot and the engine is a clear way in which pilot decision making could be enhanced and flight outcome improved. It has been highlighted that pilots can often encounter symptoms of startle or surprise following unexpected events, including engine damage following a bird strike that can lead to impaired performance and potentially life threating failures. Remedial measures to prevent such failures from occurring are therefore of great importance.

With the greatest number of predicted failures being classified as communication failures, it is vital that remedial measures focus on assisting flight crew coordination and communication. However, it is important to remember that 'communication' as a term carries a variety of meaning as it may be written, verbal, non-verbal, face-to-face and/or remote (Kanki, 2019). In the context of a bird strike, there are numerous mitigation strategies that could be used to facilitate pilot communication. For instance, the addition of an engine damage notification would support flight crews during initial diagnosis of abnormal engine parameters. Pilots have been found to spend much of their time head-down during flight, which reduces their situation awareness and limits their contextual information including awareness for other traffic, potential hazards and obstructions (Wilkins, 2018). Thus, even if the flight crew failed to check their external environment following take-off, an engine damage notification would prompt the flight crew to check their engine system parameters. For any engine damage notification, it would be important to use relevant colour conventions to convey criticality (e.g., red for severe damage and amber for moderate damage). This could then be used to provide a clear and immediate indication of engine status. Further, to avoid having to retrieve and locate the most appropriate checklist from the QRH, relevant engine damage checklists could be automatically presented to the flight crew. This would be especially beneficial, if for example, fuel jettisons were required and time permitted. Given the complexity of the scenario, as the crew progresses through the checklist, visible feedback of progress would be helpful. This means that any interruptions (e.g., communications with Air Traffic Control) would not disrupt progress within the checklist. The addition of lighting to flight deck controls would also support the flight crew in navigating through their way through the checklists, and assist in guiding them towards what needs to be done next. This may be particularly useful in such a high workload scenario, such as engine damage during take-off, but more research is required to assess the utility of such a measure.

The analysis also highlighted the possibility for failure when flight crews have to determine performance calculations. In order to overcome this, the aircraft itself could provide an indication of engine performance using sensor-based technology. This may be achieved visually via some form of indication on the primary flight display and navigation display, or numerically so that data can be inputted into the appropriate systems directly. A review page could also help remind the crew what steps have been taken, what is left to do and the impact on any action on engine system parameters. A summary of remedial measures, matched to failure failures is presented in Table 4.

Table 4. Example remedial measures matched to failures

Failure	**Remedial measure(s)**
Failure to check for engine fluctuations	Aircraft is able to automatically notify flight crew of any abnormal engine fluctuations / increase saliency of parameters (i.e., make display larger / automatically provide trend data). Use standard colour conventions to convey criticality in written display messages (i.e., red for ‘severe damage’, amber for ‘damage’)
Failure to check for any missing parameters	Directly inform crew of engine damage via HMI
Failure to verbalise any abnormalities	Aircraft is able to automatically annunciate any abnormalities to increase the saliency of abnormal system parameters
Failure to retrieve and follow the correct procedure within the QRH	Enable aircraft displays to automatically present most relevant checklist on screen removing the need for PM to access physical QRH
Failure to communicate effectively to verify the situation	Allow aircraft to display “engine FOD” notification to assist in diagnosis Ensure adequate Crew Resource Management is in place to ensure adequate cross checking procedure as a standard working practise
Failure to agree on appropriate action	Incorporate a review page to provide trend data to support the assessment / review of the actions that have been taken.
Failure to use appropriate controls	Allow aircraft to guide pilots to appropriate controls in emergency sequence through use of lighting.
Failure to complete performance calculations	Enable aircraft to automatically calculate performance based on current engine data. Present to flight crew with option to accept or reject.

General Discussion

This paper represents one of the first of its kind in providing an evaluation and discussion of the types of failures that flight crews can make when attempting to manage engine damage on take-off due to an engine bird strike event. Some of which have been seen to occur in real life. A hypothetical scenario of an engine bird strike event was developed and HTA and SHERPA methodologies were applied. This enabled the proposal of new ways in which flight crew may be better supported. In line with previous research on real-world systems (Parnell et al., 2019), the analysis reveals relatively low levels of criticality (i.e., no highly likely or highly critical failures identified), Even so, Parnell et al. (2019) stress that it is still important to consider how the design of a system can reduce the possibility of failures occurring which could otherwise have adverse safety implications for the flight. Remedial measures to some of the key failures identified within the SHERPA (Table 4) demonstrate how flight deck instrumentation and enhanced displays may be used in the future to minimise the prevalence of the failures identified. This is in contrast to the traditional approach of relying upon Crew Resource Management to mitigate and protect against communication failures. Thus, the SHERPA analysis demonstrates that there are alternative ways in which communication on the flight deck can be improved using technological devices.

It is anticipated that new algorithms can be integrated into the cockpit that provide accurate, reliable and up-to-date information regarding the status of the aircraft engines and presented to the flight crew in a clear and transparent way (Parnell et al., 2019). However, the impact of startle (Bradley et al., 1993; Martin et al., 2015) and surprise (Hortsmann, 2006; Rivera et al., 2014) must not be overlooked. The relevance of startle and surprise to the failures arising from unexpected incidents such as engine damage on take-off due to bird strikes has been highlighted here. Yet, further research is needed to assess the desirability and utility of the approaches outlined in this paper, taking into consideration the impact of startle and surprise. Previous literature has highlighted that a pilot's ability to detect, recognise and respond to unannounced and unexpected problems, i.e., surprising events, is significantly hindered compared to their ability to complete standard flight operations (Beringer & Harris, 1999; Casner et al., 2013; Martin et al., 2016).

Whilst the focus of this paper has been on engine damage on take-off following a bird strike, the remedial measures proposed will also be applicable to other engine FOD events. For instance, in December 2018, Gatwick Airport was forced to close due to the presence of a drone within the restricted zone of the aerodrome (Haylen, 2019). Despite the usage of drones being prohibited around airports, the International Air Transport Association (2016) caution that drones pose a serious safety risk to aircraft and that in the event of collision or near miss, could result in loss of life. A high-speed collision between an aircraft and a drone would likely cause more severe engine damage than a bird strike. However, any engine FOD strike requires the flight crew to determine the aircrafts operational status. Thus, it is easy to envisage the value of an engine FOD notification as suggested across scenarios.

As these systems are developed, care must be taken so that new sources of failure are not introduced. More research is required to assess the extent to which safety is maintained, improved or compromised with the addition of new technology. Thus, the failures identified within the SHERPA analysis should be continually reviewed throughout the design and development process. Indeed, there may be other solutions, and failures, that have yet to be identified within the parameters of the presented study. Furthermore, the effectiveness of the remedial measures proposed are likely to be dependent on the specific event itself which, as noted in the introduction, can be highly variable. Thorough testing across different scenarios will therefore be required of any novel technology.

Next steps

The remedial measures generated from this analysis are under review by an aerospace engineering manufacturer who is looking to utilise the outputs to inform a future interface which convey engine health to the airline pilot. This interface aims to improve pilot decision making, minimise flight disruptions and improve flight safety. The outputs of this analysis provide valid and usable findings that identify how current processes can be enhanced through future technologies. A comparison between 'work-as-done', as presented by the HTA, and 'work-as-envisaged' should be the focus of the next stage of research. Otherwise, there is a risk that the expected benefits of the new technology are unlikely to be realised in reality (Damodaran, 1996).

Conclusion

In line with recommendations from the NTSB (2010), new technology is being developed that is capable of keeping commercial airline pilots informed about the continuing operational status of an aircraft engine following a FOD strike event. In order to explore the information and design requirements of such a system, HTA and SHERPA was applied to look more closely at current operational practise. These methods enable deficiencies within the current system to be more easily identified and facilitate discussion on the design of new measures that can minimise the opportunity for failure to occur (Harris et al., 2005). Whilst the current analysis yielded a large number of potential failures, it is clear that enhanced interface technologies could be an effective in supporting aircrew (Lane et al., 2006). Future work should focus on determining the applicability of these remedial measures to meet the NTSB (2010) recommendation of keeping pilots informed about the continuing operational status of the engine following a FOD strike.

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Appendix

Task(n)	Task name	Failure	Failure consequence	Likelihood	Criticality	Remedial measure
1.1.	Look for flock of birds	A8	Flight crew unaware of the presence of birds	L	L	A/C equipped with sensor systems to identify potential FOD (e.g., birds / drones etc.).
1.2.	Listen for impact of birds on the flight deck	R1	Flight crew unaware that strike has occurred	M	L	Automatically notify the crew of an engine strike through new HMI on the flight deck (e.g., "Bird Strike")
1.3.	Observe for engine fluctuations	C1	Flight crew do not check for engine flucutations	L	M	Notify flight crew of any abnormal engine fluctuations / increase saliency of parameters (i.e., make display larger / automatically provide trend data)
1.4.	Select A/P button	A6	May select wrong button	L	M	Highlight auto throttle button / increase size of button
		A8	Flight crew would experience significant levels of vibration and noise	L	M	Automatically select auto pilot
2.1. 1.	Read temperature levels	C1	Flight crew unaware of engine temperature	L	L	Prompt flight crew to check temperature (e.g., auditory prompt / visual prompt)
		C3	Flight crew may misunderstand the situation	L	M	Increase saliency of critical information (e.g., red box items / make display larger)
		A8	Flight crew unaware of engine temperature	L	L	Prompt flight crew to check temperature (e.g., auditory prompt / visual prompt)
		R1	Flight crew unaware of engine temperature	L	L	Prompt flight crew to check temperature (e.g., auditory prompt / visual prompt)
		R2	Flight crew may misunderstand the situation	L	M	Increase saliency of critical information (e.g., red box items / make display larger)
2.1. 2.	Read pressure levels	C1	Flight crew unaware of pressure levels	L	L	Prompt flight crew to check engine pressure (e.g., auditory prompt / visual prompt)

		C3	Flight crew may misunderstand the situation	L	M	Increase saliency of critical information (e.g., red box items / make display larger)
		A8	Flight crew unaware of pressure levels	L	L	Prompt flight crew to check engine pressure (e.g., auditory prompt / visual prompt)
		R1	Flight crew unaware of pressure levels	L	L	Prompt flight crew to check engine pressure (e.g., auditory prompt / visual prompt)
		R2	Flight crew may misunderstand the situation	L	M	Increase saliency of critical information (e.g., red box items / make display larger)
2.1.3.	Read vibration levels	C1	Flight crew unaware of vibration levels	L	L	Prompt flight crew to check engine vibration (e.g., auditory prompt / visual prompt)
		C3	Flight crew may misunderstand the situation	L	M	Increase saliency of critical information (e.g., red box items / make display larger)
		A8	Flight crew unaware of vibration levels	L	L	Prompt flight crew to check engine vibration (e.g., auditory prompt / visual prompt)
		R1	Flight crew unaware of vibration levels	L	L	Prompt flight crew to check engine vibration (e.g., auditory prompt / visual prompt)
		R2	Flight crew may misunderstand the situation	L	M	Increase saliency of critical information (e.g., red box items / make display larger)
2.1.4.	Check rotation of engine (N1/N2)	C1	Flight crew unaware of engine status	L	M	Increase saliency of critical information (e.g., directly inform crew of engine damage via HMI)
		C3	Flight crew unaware of engine status	L	M	Increase saliency of critical information (e.g., directly inform crew of engine damage via HMI)
		R1	Flight crew unaware of engine status	L	M	Increase saliency of critical information (e.g., directly inform crew of engine damage via HMI)
		R2	Flight crew unaware of engine status	L	M	Increase saliency of critical information (e.g., directly inform crew of engine damage via HMI)
2.1.5.	Check for presence of a fire warning	C1	Flight crew unaware of engine status	L	M	Increase saliency of critical information (e.g., directly inform crew of engine damage via HMI)
		C3	Flight crew unaware of engine status	L	M	Increase saliency of critical information (e.g., directly inform crew of engine damage via HMI)
		R1	Flight crew unaware of engine status	L	M	Increase saliency of critical information (e.g., directly inform crew of engine damage via HMI)

		R2	Flight crew unaware of engine status	L	M	Increase saliency of critical information (e.g., directly inform crew of engine damage via HMI)
2.1.6.	Check for presence of any missing parameters	C1	Flight crew unaware of engine status	L	M	Increase saliency of critical information (e.g., directly inform crew of engine damage via HMI)
		C3	Flight crew unaware of engine status	L	M	Increase saliency of critical information (e.g., directly inform crew of engine damage via HMI)
		R1	Flight crew unaware of engine status	L	M	Increase saliency of critical information (e.g., directly inform crew of engine damage via HMI)
		R2	Flight crew unaware of engine status	L	M	Increase saliency of critical information (e.g., directly inform crew of engine damage via HMI)
2.1.7.	Check for presence of significant airframe vibration	R1	Flight crew have an incomplete understanding of airframe status	L	M	Use colour to denote criticality of situation in any notification (e.g., red for severe, amber for warning) / use appropriate warning text (e.g., SEVERE or DAMAGE)
2.1.8.	Check for presence of EICAS/ECAM warnings	I3	Flight crew may not have complete shared situation awareness	L	H	Automatically annunciate any abnormalities / increase saliency of abnormal system parameters
		A8	Unaware of critical aircraft status	L	H	Increase saliency of warning to ensure critical information is most prominent
		C1	Unaware of critical aircraft status	L	H	Increase saliency of warning to ensure critical information is most prominent
		R1	Unaware of critical aircraft status	L	H	Increase saliency of warning to ensure critical information is most prominent
2.1.9.	Verbalise any abnormalities	I1	Flight crew do not have a shared situation awareness	L	H	Automatically annunciate any abnormalities / increase saliency of abnormal system parameters
		I2	Flight crew may have conflicting situation awareness	L	H	Automatically annunciate any abnormalities / increase saliency of abnormal system parameters
		I3	Flight crew may not have complete shared situation awareness	L	H	Automatically annunciate any abnormalities / increase saliency of abnormal system parameters
3.1.1.b.	Verbalise interaction to enact pre-flight briefing	I1	Decision to enact pre-flight briefing is not made resulting	L	H	Automatic prompt to encourage pilots to act (i.e., mechanism to try and overcome any startle effect)

			in flight crew not have a shared situation awareness			
3.1. 2.b.	Hear co-pilot acknowledgement	R1	Acknowledgement not heard resulting in delay to action	L	M	
		R3	Acknowledgement not heard resulting in delay to action	L	M	
3.1. 3.1. b.	Press PTT button	A8	Information is not shared with ATC	L	H	Automatically create communication link to ATC should the aircraft suffer any abnormal reading or emergancy conditions
3.1. 3.2. b.	Talk to ATC	I1	Information is not shared with ATC	L	H	Automatically create communication link to ATC should the aircraft suffer any abnormal reading or emergancy conditions
		I3	Incomplete data sharing between flight crew and ATC	L	H	
3.1. 4.3. a.	Release PTT button	A8	Channel remains open	L	L	Remind flight crew that channel is still open
3.1. 4.b.	Climb to MSA	A8	Risk of altering system parameters below MSA	L	H	*(In some situations, flight crew will be unable to climb to MSA due to engine damage. Here, we assume that they could reach MSA)* - Remedial measure = provide notification of climb performance / limitation on ability of aircraft to reach MSA
3.1. 5.b.	Hear request for QRH	R1	Request not heard action	L	M	Automatically present most relevant checklist on screen removing the need for co-pilot to access physical QRH
3.1. 6.b.	Retrieve QRH from storage	R3	Request not heard action	L	M	Automatically present most relevant checklist on screen removing the need for co-pilot to access physical QRH
3.1. 7.b.	Select appropriate page	A8	Risk of not following procedures correctly	L	H	Ensure adequate and realistic training to minimise startle effect and allow crew to follow procedures
		R2	May look at wrong checklist for current situation	L	H	Automatically present relevant pages / checklists from QRH in an electronic device
3.1. 8.1. b	Place hand on auto throttle arm switch on engine X	A6	May place hand on wrong control	L	M	Ensure frequent recurrent training on different aircraft types to ensure Pilots are always aware of location of flight instrumentation

		A8	May not place hand on auto throttle arm switch	L	M	Prompt pilot to use relevant controls. Use LED lighting to illuminate controls on the flight deck
		S2	May select wrong auto throttle arm switch	L	M	Ensure frequent recurrent training on different aircraft types to ensure Pilots are always aware of location of flight instrumentation
3.1. 8.2. b.	Verify correct arm switch has been selected	I1	Cross check is not completed	L	M	Ensure adequate CRM in training to ensure adequate cross checking procedure are in place as a standard working parctice
		I2	Wrong information is communicated so flight crew may have conflicting situation awareness	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness
3.1. 8.3. b.	Auto throttle OFF	A8	Auto throttle remains on	L	H	
3.1. 8.4. b.	Place hand on thrust lever on engine X	A6	May place hand on wrong control	L	M	Ensure frequent recurrent training on different aircraft types to ensure Pilots are always aware of location of flight instrumentation
		A8	May not place hand on thrust lever	L	M	
		S2	May select wrong thrust lever	L	M	Ensure frequent recurrent training on different aircraft types to ensure Pilots are always aware of location of flight instrumentation
3.1. 8.5. b.	Verify correct thrust lever has been selected	I1	Cross check is not completed	L	M	Ensure adequate CRM in training to ensure adequate cross checking procedure are in place as a standard working parctice
		I2	Wrong information is communicated so flight crew may have conflicting situation awareness	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness
3.1. 8.6. b.	IDLE thrust lever	A8	Automatic thrust control remains active	L	M	

3.1.8.7.b.	Place hand on fuel control switch on engine X	A6	May place hand on wrong control	L	M	Ensure frequent recurrent training on different aircraft types to ensure Pilots are always aware of location of flight instrumentation
		A8	May not place hand on thrust lever	L	M	
		S2	May select wrong thrust lever	L	M	Ensure frequent recurrent training on different aircraft types to ensure Pilots are always aware of location of flight instrumentation
3.1.8.8.b.	Verify correct fuel control switch has been selected	I1	Cross check is not completed	L	M	Ensure adequate CRM in training to ensure adequate cross checking procedure are in place as a standard working parctice
		I2	Wrong information is communicated so flight crew may have conflicting situation awareness	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness
3.1.8.9.b.	CUT OFF fuel control switch	A8	Engine remains ignited	L	M	
3.1.8.10.b.	Place hand on engine fire switch on engine X	A6	May place hand on wrong fire switch	L	M	Ensure frequent recurrent training on different aircraft types to ensure Pilots are always aware of location of flight instrumentation
		A8	May not place hand on fire switch	L	M	
		S2	May select wrong fire switch	L	M	Ensure frequent recurrent training on different aircraft types to ensure Pilots are always aware of location of flight instrumentation
3.1.8.11.b.	Verify correct engine fire switch has been selected	I1	Cross check is not completed	L	M	Ensure adequate CRM in training to ensure adequate cross checking procedure are in place as a standard working parctice
		I2	Wrong information is communicated so flight crew may have conflicting situation awareness	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness

3.1.8.12.b.	PULL engine fire switch	A8	Fuel flow to the engine continues and extinguisher fluid is not triggered	L	M	
3.1.8.13.b.	Place hand on APU selector	A8	May not place hand on APU selector	L	M	
3.1.8.14.b	Push APU selector START	A8	May not start APU	L	M	Automatically start APU if airborn and insufficent power is being generated by engine
		S2	May select wrong function on APU	L	M	
3.1.8.15.b.	Push APU selector ON	A8	May not start APU - no power reinstalled to aircraft	L	M	Automatically start APU if airborn and insufficent power is being generated by engine
		S2	May select wrong function on APU	L	M	
3.1.8.16.b.	Place hand on transponder mode selector	A8	May not place hand on transponder mode selector	L	M	
3.1.8.17.b.	Select TA ONLY	I1	Other aircraft remain unaware of critical situation (i.e., aircraft performance issues)	L	M	
		S1	Do not select TA only mode so other aircraft unaware of performance issues	L	M	Automatically select 'TA only' mode. Ensure mode state is obvious to the flight crew via some form of HMI
		S2	Wrong mode selected	L	M	Automatically select 'TA only' mode. Ensure mode state is obvious to the flight crew via some form of HMI
4.1.	Look at engine page	A8	Pilot does not look at engine page	L	M	Automatically select 'TA only' mode. Ensure mode state is obvious to the flight crew via some form of HMI
4.2.	Read displays	C1	Unaware of the impact of prior actions already taken	L	M	

		C3	Erroneous view of the impact of prior actions already taken	L	M	Automatically identify abnormal system parameters (e.g., increase size of displays). Provide data trend to enable pilots to assess impact of any prior action
		A8	Unaware of the impact of prior actions already taken	L	M	Automatically identify abnormal system parameters (e.g., increase size of displays). Provide data trend to enable pilots to assess impact of any prior action
		R1	Unaware of the impact of prior actions already taken	L	M	Automatically identify abnormal system parameters (e.g., increase size of displays). Provide data trend to enable pilots to assess impact of any prior action
		R2	Erroneous view of the impact of prior actions already taken	L	M	Automatically identify abnormal system parameters (e.g., increase size of displays). Provide data trend to enable pilots to assess impact of any prior action
4.3.	Check status of the EICAS / ECAM	I3	Flight crew may not have complete shared situation awareness	L	H	Automatically annunciate any abnormalities / increase saliency of abnormal system parameters
		A8	Unaware of critical aircraft status	L	H	Increase saliency of warning to ensure critical information is most prominent
		C1	Unaware of critical aircraft status	L	H	Increase saliency of warning to ensure critical information is most prominent
		R1	Unaware of critical aircraft status	L	H	Increase saliency of warning to ensure critical information is most prominent
4.4.1.	Look at PFD	A8	Flight crew unaware of current speed and altitude	L	M	For PF, declutter flight deck. Make PFD and ND larger and more salient.
4.4.2.	Check speed	C1	Flight crew unaware of current speed	L	H	Highlight any under performance in aircraft performance. Notify crew using bold colour (e.g., red) if climb performance does not match progress against desired altitude on Primary Flight Display and Navigation Display
		R1	Flight crew unaware of current speed	L	H	Highlight any under performance in aircraft performance. Notify crew using bold colour (e.g., red) if climb performance does not match progress against desired altitude on Primary Flight Display and Navigation Display
4.4.3.	Check altitude	C1	Flight crew unaware of current altitude	L	H	Highlight any under performance in aircraft performance. Notify crew using bold colour (e.g., red) if climb performance does not match

						progress against desired altitude on Primary Flight Display and Navigation Display
		R1	Flight crew unaware of current altitude	L	H	Highlight any under performance in aircraft performance. Notify crew using bold colour (e.g., red) if climb performance does not match progress against desired altitude on Primary Flight Display and Navigation Display
5.1.1.	Verify situation	I1	Flight crew do not have a shared situation awareness	L	M	Highlight any under performance in aircraft performance. Notify crew using bold colour (e.g., red) if climb performance does not match progress against desired altitude
		I2	Flight crew may have conflicting situation awareness	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness
		I3	Flight crew may not have complete shared situation awareness	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness
5.1.2.	Verify actions taken	I1	Flight crew do not have a shared situation awareness	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness
		I2	Flight crew may have conflicting situation awareness	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness
		I3	Flight crew may not have complete shared situation awareness	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness
5.1.3.	Verify agreement	I1	Flight crew may not agree	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness
		I2	Flight crew may not agree	L	M	Ensure adequate CRM in training to manage disagreements
		I3	Flight crew may not agree	L	M	Ensure adequate CRM in training to manage disagreements
5.2.1.	Look at ND to determine current location	C1	Flight crew unaware of their current location	L	M	Ensure adequate CRM in training to manage disagreements
5.2.2.	Check current location	C1	Flight crew unaware of their current location	L	M	Increase size of ND / use colour to highlight current location on display
5.2.4.1.	Look at flight plan or FMC	A8	Do not check alternative airports	L	M	Increase size of ND / use colour to highlight current location on display

5.2.4.2.	Check distance	C1	Flight crew unaware of distance to alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
		R1	Flight crew unaware of distance to alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
		R2	Flight crew have inaccurate knowledge about distance to alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
5.2.4.3.	Check maintenance facilities	C1	Flight crew unaware of maintenance facilities at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
		R1	Flight crew unaware of maintenance facilities at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
		R2	Flight crew have inaccurate knowledge about maintenance facilities at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
5.2.4.4.	Check emergency facilities	C1	Flight crew unaware of emergency facilities at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
		R1	Flight crew unaware of emergency facilities at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
		R2	Flight crew have inaccurate knowledge about emergency facilities at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
5.2.4.5.	Check weather	C1	Flight crew unaware of weather at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
		R1	Flight crew unaware of weather at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements

		R2	Flight crew have inaccurate knowledge about weather at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
5.2.4.6.	Check runway length	C1	Flight crew unaware of runway length at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
		R1	Flight crew unaware of runway length at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
		R2	Flight crew have inaccurate knowledge about runway length at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
5.2.4.7.	Check approach type	C1	Flight crew unaware of approach type at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
		R1	Flight crew unaware of approach type at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
		R2	Flight crew have inaccurate knowledge about approach type at alternative airport	L	M	Automatically present a list of possible alternatives, automatically prioritised based on current aircraft performance and landing requirements
5.2.5.	Verify appropriate landing site	I1	Flight crew do not have a shared situation awareness	L	M	Automatically prompt fligth crew to discuss their chosen landing site when entering details into FMC
		I2	Flight crew may have conflicting situation awareness	L	M	Automatically prompt fligth crew to discuss their chosen landing site when entering details into FMC
5.3.1.1.1.	Press PTT button	A8	Message does not get through to ATC	L	H	Allow ATC to automatically see abnormal aircraft system readings
5.3.1.1.2.1.	Verbalise nature of the problem	I1	ATC unaware of the nature of the problem	L	M	Automatically create communication link to ATC should the aircraft suffer any abnormal reading or emergancy conditions
		I2	ATC provided with incorrect information	L	M	Allow ATC to automatically see abnormal aircraft system readings

		I3	ATC have incomplete understanding of the problem	L	M	Allow ATC to automatically see abnormal aircraft system readings and FMS/FMC
5.3. 1.1. 2.2.	Notify ATC of intentions	I1	ATC unaware of pilots intentions	L	M	
		I2	ATC provided with incorrect information	L	M	
		I3	ATC have incomplete understanding of the actions to be taken	L	M	
5.3. 1.1. 2.3.	Provide indication of time	I1	ATC unaware of time constraints on flight crew	L	M	
		I2	ATC provided with incorrect information regarding time constraints	L	M	
5.3. 1.1. 2.4.	Request special precautions	I1	ATC unaware of special precautions e.g. emergency service	L	M	Adapt ATC procedure so that special precautions are always in place in the case of aircraft emergency return
5.3. 1.1. 3.	Release PTT button	A8	Channel remains open	L	L	Remind flight crew that channel is still open
5.3. 1.2. 1.	Press PTT button	A8	Message does not get through to cabin crew	L	M	
5.3. 1.2. 2.1.	Verbalise nature of the problem	I1	Cabin crew unaware of the nature of the problem	L	M	Enable Cabin Crew to prompt flight deck for information if aircraft is not acting as expected/ evidence for change of flight plan
		I2	Cabin crew are provided with incorrect information	L	M	
		I3	Cabin crew have incomplete understanding of the problem	L	M	Enable Cabin Crew to prompt flight deck for clarification of information if aircraft is not acting as expected

5.3.1.2.2.2.	Notify cabin crew of intentions	I1	Cabin crew unaware of pilots intentions	L	M	Enable Cabin Crew to prompt flight deck for clarification of information if aircraft is not acting as expected
		I2	Cabin crew provided with incorrect information	L	M	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
		I3	Cabin crew have incomplete understanding of the actions to be taken	L	M	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
5.3.1.2.2.3.	Provide indication of time	I1	Cabin crew unaware of time constraints for landing	L	M	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
		I2	Cabin crew provided with incorrect information regarding time until landing	L	M	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
5.3.1.2.2.4.	Notify of any special precautions requested	I1	Cabin crew unaware of any special precautions e.g. emergency services present on landing	L	M	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
5.3.1.3.1.	Press PTT button	A8	Message does not get through to passengers	L	L	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
5.3.1.2.1.	Verbalise nature of the problem	I1	Passengers unaware of the nature of the problem	L	L	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
		I2	Passengers are provided with incorrect information	L	L	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
		I3	Passengers have incomplete understanding of the problem	L	L	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
5.3.1.2.2.	Notify passengers of intentions	I1	Passengers unaware of intentions	L	L	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
		I2	Passengers provided with incorrect information	L	L	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required

		I3	Passengers have incomplete understanding of the actions to be taken	L	L	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
5.3.1.2.3.	Provide indication of time	I1	Passengers unaware of time constraints for landing	L	L	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
		I2	Passengers provided with incorrect information regarding time until landing	L	L	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
5.3.1.2.4.	Notify of any special precautions requested	I1	Passengers unaware of any special precautions requested	L	L	Trigger post event notification/ digital checklist to ensure that flight crew are promted to complete all non-critical tasks required
5.3.1.2.3.	Release PTT button	A8	Channel remains open	L	L	Remind flight crew that channel is still open
5.3.1.4.1.	Calculate performance calculations	A8	Performance calculations are not generated	L	M	Enable aircraft to automatically calculate performance based on current situation. Present to flight crew with option to accept or reject. Provide an indication of engine status
		R2	Performance calculations inaccurate which will affect judgement on approach	L	H	Enable aircraft to automatically calculate performance based on current situation. Present to flight crew with option to accept or reject. Provide an indication of engine status
5.3.1.4.2.1.1.	Place hand on fuel jettison arm switch	A6	May place hand on wrong control	L	M	Ensure frequent recurrent training on different aircraft types to ensure Pilots are always aware of location of flight instrumentation
		A8	May not place hand on fuel jettison arm switch	L	M	Guide pilots to appropriate controls / sequence through use of lighting
		S2	May select wrong fuel jettison arm switch	L	M	Ensure frequent recurrent training on different aircraft types to ensure Pilots are always aware of location of flight instrumentation
5.3.1.4.2.1.2.	Switch fuel jettison arm switch to ARMED	A8	Unable to complete fuel jettison	L	M	Notify flight crew if fuel jettison is required on screen. This may form part of an 'options available' page that helps pilots deal with bird strike event / if jettison is appropriate automatically present relevant pages from QRH

5.3.1.4.2.1.3.	Place hand on fuel to remain selector	A8	Unable to complete fuel jettison	L	M	Notify flight crew if fuel jettison is required on screen. This may form part of an 'options available' page that helps pilots deal with bird strike event / if jettison is appropriate automatically present relevant pages from QRH
5.3.1.4.2.1.4.	Pull on fuel to remain selector	A8	Unable to complete fuel jettison	L	M	Notify flight crew if fuel jettison is required on screen. This may form part of an 'options available' page that helps pilots deal with bird strike event / if jettison is appropriate automatically present relevant pages from QRH
5.3.1.4.2.1.5.	Set manually	A4	May programme to jettison too much / too little fuel	L	H	Prompt flight crew to confirm their selection
5.3.1.4.2.1.6.	IDLE thrust lever	A8	Unable to complete fuel jettison	L	M	Notify flight crew if fuel jettison is required on screen. This may form part of an 'options available' page that helps pilots deal with bird strike event / if jettison is appropriate automatically present relevant pages from QRH
5.3.1.4.2.1.7.	Turn jettison nozzle valve switches ON	A8	Unable to complete fuel jettison / will land over weight	L	M	Notify flight crew if fuel jettison is required on screen. This may form part of an 'options available' page that helps pilots deal with bird strike event / if jettison is appropriate automatically present relevant pages from QRH
5.3.1.4.2.1.8.	Wait until fuel jettison is complete	A2	May not wait for the appropriate amount of time	L	M	Provide an indication of how long the fuel jettison will take (e.g., notification of time remaining until complete)
5.3.1.4.2.1.9.	Place hands on fuel jettison nozzle valve switches	A8	May not place hand on fuel jettison nozzle valve	L	M	Guide pilots to appropriate controls / sequence through use of lighting
5.3.1.4.2.1.10.	Turn jettison nozzle valve switches OFF	A2	May switch off too early / late	L	M	
		A8	May lose too much fuel	L	H	

5.3.1.4.2.1.11.	Place hand on fuel to remain selector	A8	May not place hand on fuel to remain selector	L	M	Guide pilots to appropriate controls / sequence through use of lighting
5.3.1.4.2.1.12.	Set fuel to remain selector OFF	A2	May switch off too early / late	L	M	
5.3.1.4.2.1.13.	Place hand on fuel jettison arm switch	A6	May place hand on wrong control	L	M	Ensure frequent recurrent training on different aircraft types to ensure Pilots are always aware of location of flight instrumentation
		A8	May not place hand on fuel jettison arm switch	L	M	Guide pilots to appropriate controls / sequence through use of lighting
		S2	May select wrong fuel jettison arm switch	L	M	Ensure frequent recurrent training on different aircraft types to ensure Pilots are always aware of location of flight instrumentation
5.3.1.4.2.1.14.	Switch fuel jettison arm switch to OFF	A2	May switch off too early / late	L	M	
5.3.1.4.2.2.1.	Look at tuning and control panel	A8	May lead to additional failures as outlined below in 5.3.1.4.2.1.2.2.b.	L	M	Guide pilots to appropriate controls / sequence through use of lighting
5.3.1.4.2.2.2.	Place hand on GPWS FLAP OVRD	A6	May place hand on wrong button	L	M	Guide pilots to appropriate controls / sequence through use of lighting
		A8	Pilot does not place hand on GPWS FLAP OVRD	L	M	
5.3.1.4.	OVRD	A8	Pilot does not override GPWS FLAP	L	M	

2.2.3.						
5.3.1.4.2.1.	Load performance calculations into FMC	A8	Performance calculations are not entered into FMC	L	M	Enable aircraft to automatically calculate performance based on current situation. Present to flight crew with option to accept or reject. Provide an indication of engine status
		I2	Inaccurate performance calculations loaded into FMC	L	H	Enable aircraft to automatically calculate performance based on current situation. Present to flight crew with option to accept or reject. Provide an indication of engine status
5.3.1.4.2.2.	Perform briefing	I1	Flight crew do not have a shared situation awareness	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness
		I2	Flight crew may have conflicting situation awareness	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness
		I3	Flight crew may not have complete shared situation awareness	L	M	Ensure adequate CRM in training to ensure adequate commication to embed situation awareness
5.3.1.4.2.3.1.	Press PTT button	A8	Information is not shared with ATC	L	M	
5.3.1.4.2.3.2.	Talk to ATC	I1	Information is not shared with ATC	L	M	
		I3	Incomplete data sharing between flight crew and ATC	L	M	
5.3.1.4.2.3.3.	Release PTT button	A8	Channel remains open	L	L	Remind flight crew that channel is still open
5.4.1.	Discuss what has happened	I1	Flight crew do not have a shared situation awareness	L	M	Incorporate a review page to provide trend data to support the assessment / review of the actions that have been taken.

		I2	Flight crew may have conflicting situation awareness	L	M	Incorporate a review page to provide trend data to support the assessment / review of the actions that have been taken.
		I3	Flight crew may not have complete shared situation awareness	L	M	Incorporate a review page to provide trend data to support the assessment / review of the actions that have been taken.
5.4.2.	Discuss actions taken	I1	Flight crew do not have a shared situation awareness	L	M	Incorporate a review page to provide trend data to support the assessment / review of the actions that have been taken.
		I2	Flight crew may have conflicting situation awareness	L	M	Incorporate a review page to provide trend data to support the assessment / review of the actions that have been taken.
		I3	Flight crew may not have complete shared situation awareness	L	M	Incorporate a review page to provide trend data to support the assessment / review of the actions that have been taken.
5.4.3.1.	Discuss go-around procedure	I1	Flight crew do not have a shared situation awareness	L	M	Incorporate a review page that prompts pilots to discuss next set of actions
		I2	Flight crew may have conflicting situation awareness	L	M	Incorporate a review page that prompts pilots to discuss next set of actions
		I3	Flight crew may not have complete shared situation awareness	L	M	Incorporate a review page that prompts pilots to discuss next set of actions
5.4.3.2.	Discuss potential for loss of second engine	I1	Flight crew do not have a shared situation awareness	L	M	Incorporate a review page that prompts pilots to discuss next set of actions
		I2	Flight crew may have conflicting situation awareness	L	M	Incorporate a review page that prompts pilots to discuss next set of actions
		I3	Flight crew may not have complete shared situation awareness	L	M	Incorporate a review page that prompts pilots to discuss next set of actions
5.4.3.3.	Discuss what has been arranged upon landing (e.g. emergency services)	I1	Flight crew do not have a shared situation awareness	L	M	Incorporate a review page to provide trend data to support the assessment / review of the actions that have been taken.
		I2	Flight crew may have conflicting situation awareness	L	M	Incorporate a review page to provide trend data to support the assessment / review of the actions that have been taken.

		I3	Flight crew may not have complete shared situation awareness	L	M	Incorporate a review page to provide trend data to support the assessment / review of the actions that have been taken.