Pilot decision-making during a dual engine failure on take-off: Insights from three different decision-making models

Abstract

Commercial airline pilots are required to make efficient, justifiable and safety-critical decisions when faced with adverse events such as engine failures. Although these are rare events, the consequences are severe, and the pilot response is critical. This paper reviews pilot decision-making when faced with a dual engine failure on take-off using three different decision models; the Recognition Primed Decision Model, Decision Ladders and the Perceptual Cycle Model. In-depth interviews with eight experienced airline pilots were conducted to capture their decision-making processes in response to a dual engine failure on take-off event. The analysis of these interviews using the three different decision models provide recommendations for a proposed decision assistant. The different decision models are discussed in relation to the insight they can bring to developing a future decision assistant tool within the flight deck of commercial aircraft.

KEYWORDS: Decision making, Recognition Primed Decision Model, Perceptual Cycle Model, Decision Ladder, Aviation, Decision assistant

1. Introduction

Commercial airline pilots have a responsibility for the safety of all their passengers. Many of the safety related decisions that airline pilots make are routine in nature, however, occasionally they may be faced with safety critical events that require difficult decisions to be made under high-workload and time critical conditions. The pilots of US Airways Flight 1549, were faced with such a decision. The aircraft was climbing out of its departure airport of New York when, at approximately 2800ft and just 2 minutes after take-off, a flock of birds hit both the aircrafts' engines. This instantly caused significant damage to the engines and near total loss of thrust. This was a very serious and rare event which could have resulted in total loss of the aircraft and associated fatalities. Thankfully, the crew's decisions were a key contributing factor in the survivability of all 150 passengers and 5 crew members on board (NTSB, 2010). The pilots successfully ditched the aircraft into the Hudson River, approximately 4 minutes after the birds hit the engines and just 8.5miles from the departure airport.

The United States National Transport Safety Board (NTSB, 2010) carried out a full investigation which highlighted the importance of the pilot's decision making in the survivability of the flight. Yet, barriers were also identified that affected their ability to fully diagnose the situation and select appropriate checklists. The analysis of the pilots' decision-making in the report states that the pilots quickly called for the Quick Reference Handbook (QRH) 'Engine Dual Failure Checklist'. This checklist is intended for a total lack of thrust from the engines above 20,000ft, as this is the most likely altitude for a dual engine failure. However, in the Hudson River event neither of these criteria were met as a small amount of thrust was available and the aircraft was at 2,800ft. This meant that time available for running the checklist was severely limited. The pilots were only able to complete one third of the checklist in the time available.

Furthermore, the checklist also stated that the pilots should try to re-light the engines. The NTSB investigation identified that due to the damage to the engines they could not be re-lit. The pilots, however, did not have the information available to properly diagnose the extent of the engine damage and conclude that a re-light was not possible. The NTSB (2010) report states that 30-40 seconds were lost trying to re-light the engines. Had the pilots received more information on the operational state of the engines, they could have determined that a restart was not possible, and they may have progressed further down the 'Engine Dual Failure Checklist'.

The NTSB report highlights that many modern aircraft engines do have sensors that can be programmed to provide information on engine status, yet they are not currently used to this end. The first listed recommendation of the NTSB (2010) report was therefore "*to complete the development of a technology capable of informing pilots about the continuing operational status of* *an engine*" (p124; NTSB 2010). The development of such a system requires the pilot to be able to understand and interpret the information easily, especially in critical, high-workload situations. Human Factors insight is essential in the design process of new aviation technologies such as this, to ensure they are usable and safe while conveying complex information in a succinct manner (Harris and Stanton, 2010; Salas et al, 2010; Parnell et al, 2019 Stanton et al, 2019; CIEHF, 2020).

An aerospace manufacture is currently working with Human Factors researchers to design and develop an engine condition monitoring system, similar to that detailed in the NTSB (2010) report, to aid pilot's decisions when faced with engine failure events. Before implementing a decision assistant, it is essential that the scope of the system is reviewed to understand its integration with current decision-making procedures (Mosier & Skitka, 1997; Dorneich et al, 2017; Mosier & Manzey, 2019; Parnell et al, 2019; Banks et al, 2020a). The pilot's decision making within such a scenario also needs to be fully understood in order to design aids that can best inform them. Decision-making models can be applied to capture current decision-making process (Parnell et al, 2019; Banks et al, 2020a) and identify areas where additional assistance or guidance may improve the decision outcome (Simpson, 2001). When reviewing pilot decision-making in response to a dual engine failure event, we require a decision model that can capture critical decision-making, as well as inform recommendations for a decision aid. As there are multiple and diverging models, this work sought to apply three different decision models to identify multiple perspectives on the decision process and possible recommendations for a decision aid. These models were the Recognition Primed Decision Model (RPDM; Klein, 1989), Decision Ladders (Rasmussen, 1983) and the Perceptual Cycle Model (PCM; Neisser, 1976). These three models were chosen as they can account for decision-making under critical real world conditions and have been previously applied to the aviation domain (Hu et al, 2018; Stanton et al, 2010; Asmayawati & Nixon, 2020; Vidulich et al, 2010; Banks et al, 2020a; Plant & Stanton, 2012;2015).

The aim of this paper is to apply these decision models to interview data collected from airline pilots to understand how the models can comparatively inform the design of a decision aid that can assist the response to a dual-engine failure on take-off. These decision-making models will be introduced in turn in the next section. We then apply the qualitative interview data from commercial airline pilots to each of the decision models to understand how they capture decision making during a dual-engine failure on take-off. The models are then discussed in terms of how they can inform a decision aid. We compare and discuss the contributions of each of the decision models and summarise key design recommendations in response to the NTSB proposed requirement for a system that can update the pilot on the operational status of the engine.

2. Decision-Making Models

Human decision-making is a complex and well-established area of study, with multiple theoretical approaches. Of particular interest to this work is Naturalistic Decision Making (NDM); the study of decision-making in association with the environment that the decision occurs and the decision maker themselves (Klein, 2008; Gore et al, 2018). The field of NDM diverged from previous decision-making research at the time of its conception, which had assessed controlled, structured environments where the decision-maker was passive to the outcome (Klein, 2008). The inception of the field of NDM began with reviewing decision-making 'in the field' to understand the strategies behind natural decisions (Klein, 2008). Multiple different theories of NDM have since come to fruition (Lipshitz, 1993) and there is still much debate in the field over the best ways to conceptualise decision-making under naturalistic conditions (Lipshitz, 1993; Lipshitz et al, 2001; Neikar, 2010; Lintern, 2010). The RPDM, Decision Ladders and the PCM are now introduced in turn.

2.1 Recognition Primed Decision Model

The RPDM is a prominent decision model developed by Klein (1989). It has remained relevant over time and is still popular in its applications to decision-making in a variety of domains today (Neville et al, 2017; Hu et al, 2018; Yang et al, 2020). The RPDM proposes that decisions are made through the recognition of critical information and prior knowledge (Klein, 1989; Klein et al. 1993). If a situation can be matched to a previous event, prior experience will guide an individuals' interaction and any necessary decision-making. The RPDM (presented in Figure 1) states that decision-making is comprised of four key stages (Klein, 1989); Recognition, Situational Assessment, Mental Simulation, and Evaluation.

[Figure 1 Here]

Figure 1. The Recognition-Primed Decision Model (adapted from Klein et al, 1993)

Figure 1 shows that if the initial situation is not familiar, the decision maker should seek more information to identify familiar elements that may assist them. Once recognised, a situational understanding is generated from four central interacting factors; cues in the environment, expectations about the outcome, goals of the decision making and typical actions in response to the situation. Before the decision is actuated, it is mentally simulated to evaluate its suitability. If it is thought not to work at this stage, the process must begin again. The consideration of alternatives ends when the first satisfactory option is identified. This does not mean it is always the most suitable option, a process known as satisficing (Simon, 1955). The RPDM states that only one option can be considered at any one time, focusing on a "*moment of choice*" (p144, Klein, 1993) rather than deliberation between different options.

2.2 Decision Ladder

The Decision Ladder was developed from Rasmussen's (1983) model of cognitive control which categorises behaviour into three levels of control. Skill-based behaviour is automatic and directly interacting with the environment. Rule-based behaviour involves the stored rules and intentions that are activated by cues within the environment. Knowledge-based behaviour involves mental models and analytical problem solving using available information. Decision Ladders present the information, activities and decisions that are involved in making a decision across these three levels of behaviour. An example Decision Ladder is presented in Figure 2, the two 'streams' of the ladder flow in and out of the top section. The left side is concerned with situation analysis and the right side captures the planning, scheduling, and execution of action. At the top, the options and goals generated from situation analysis are evaluated and then selected which determines the proceeding actions that are required to be completed. The boxes within the ladder contain 'information processing activities' whereas the circles contain 'states of knowledge' resulting from the outputs of the information processing activities.

Decision Ladders map the decision as experienced by the whole system, not just the cognitive processing of the individual decision maker (Banks et al, 2020b; Stanton et al, 2017). This can allow them to be used to understand where aspects in a system can assist in improving decision-making through design (Rasmussen, 1974; Jenkins et al, 2010; Banks et al, 2020b).

[Figure 2 Here]

Figure 2. Decision Ladder framework template (adapted from Jenkins et al, 2010)

The level of behaviour used to execute a task is thought to reflect the level of expertise an individual has with the behaviour (Rasmussen, 1983). Experts are highly familiar with the situation and are therefore able to act using only skill-based behaviour without proceeding to access further knowledge. This is facilitated through 'short-cuts' across the ladder (Rasmussen, 1974; Banks et al, 2020b). Novices cannot take short-cuts as they require application of knowledge-based behaviour at the top of the ladder to understand events that are unfamiliar to them. This can also be true in situations where experts are faced with unfamiliar tasks (Vincente & Rasmussen, 1992). Figure 2 shows the two short-cut types; shunts and leaps (Stanton et al, 2017). Shortcuts from the left to the right illustrate where familiarity and expertise trigger action whereas those from right to left illustrate where desired actions require further information from the environment (McIlroy & Stanton, 2015). The direction of the shortcut is distinguished in Figure 2 with a dashed or solid line.

2.3 Perceptual Cycle Model

The PCM (Neisser, 1976) draws on Schema Theory (Bartlett, 1932) to demonstrate how the environment and context surrounding the decision interact with the cognitive structures and actions of the decision maker. Schemata are mental templates of knowledge clusters that are structured upon experiences similar in nature. They capture the commonalities that represent an experience. They provide mental templates that can inform future behaviours, as well as being fluid to updating upon exposure to new experiences. The PCM has three key components 'Schema', 'Action', 'World' which interact in a cyclic manner (see Figure 3). Schemata are active in exploring the world, interpreting it such that the knowledge structures comprising the schemata are updated to guide the exploration and interpretation of future information in the world. The individual's interaction with the world and their internal thought processes are reciprocal and influence each other (Stanton & Walker, 2011). The PCM represents both top-down and bottom-up processes. Top-down processes are directed by schemata, whereby a mental schema directions perceptual exploration and action in the world (such as anticipation of a weather event might lead a pilot to request a diversion of their route to air traffic control). Bottom-up processes are directed by events in the world, such as an alarm on the master warning panel that triggers search the pilot to determine the possible cause (if it is not a familiar warning) or enact intervention behaviour (if the warning is familiar).

[Figure 3 Here]

Figure 3. Representation of the PCM adapted from Neisser (1976)

3. Method

To populate the decision models, interviews were conducted with eight commercial airline pilots with a range of experiences. The interview reports were then used as the data source for the application of the three decision-making models.

3.1 Participants

Eight commercial airline pilots were recruited to take part in this study (3 female, 5 male), aged 29-65 (M = 39.42, SD = 14.01). All participants were qualified fixed wing ATPL or CPL pilots with an average 7085 hours flight experience (SD = 10231.72) having held their licences for an average of

13.60 years (SD = 14.28). The pilots had employment experience with thirteen different airlines and currently piloted a range of different aircraft including Airbus (n=3), Embraer (n=3) and Boeing (n=2). The study was ethically approved, and participants were reimbursed for their time. Participants were recruited until a point of saturation in the data was achieved, in which no new information was obtained for the sampling of additional pilots (Saunders et al, 2017).

3.2 Equipment

The interviews were conducted virtually using the video conferencing platform Microsoft Teams. Due to social distancing restrictions, face-to-face interviews were not an option. The participants were able to see the researchers while a PowerPoint presentation displayed the questions via the 'shared screen' tool. Microsoft Teams also allowed the interviews to be recorded in full for later analysis, subject to permission by the participant at the start of the interview.

3.3 Procedure

Semi-structured interviews were conducted by two members of the research team with one pilot at a time. They lasted approximately one hour. During each interview participants were first introduced to the outline of the interview and the wider project within which the research was being conducted. They were then presented with the engine failure scenario. This scenario features the same engine damage and altitude as the Hudson River incident (NTSB, 2010).

Engine failure scenario:

You are flying a twin-engine aircraft during its initial climb (~ 2800 feet). A flock of birds strike both engines. You must:

- *Determine the criticality of the situation (e.g., state of each engine)*
- *Take appropriate action*

The approach followed a similar method to the Critical Decision Method (CDM; Klein et al, 1989), which was developed to elicit knowledge in relation to situation awareness and decisions made within non-routine incidents (Klein et al, 1989). As detailed in the CDM procedure (Klein et al, 1989), participants were first asked to detail their initial thoughts and give an overview of the scenario in an open manner, with the option to ask for further clarifications and questions to the researchers. The researchers then went through a set of semi-structured interview probes relating to key aspects of the scenario of interest (see Appendix A). They were asked if they had any previous experience of either of the scenarios. They were also asked to detail the key actions that they would conduct, the communications they may make, their situation assessments, what aspects of the system they would be monitoring and any navigating they may be doing. The prompts aimed to capture a full account of the response to the scenario to allow the three decision-making models to be applied.

3.4 Data Analysis

The recorded interviews were transcribed using the automated transcription generated from the Microsoft Teams software. The primary researcher listened to the interviews while reading the auto-generated transcripts and amended where needed. The researcher then read through all transcripts again to fully familiarise themselves with each of the interviews.

As the pilots gave relatively similar responses due to the training they receive, and because the interviews were conducted until the point of data saturation, the interviews could be aggregated in their application to the three different models. Application of the data to the three different models was done in accordance with the guidance in the literature for each method (Klein et al, 1989; Jenkins et al, 2010; Plant & Stanton, 2016). For the purposes of the analysis presented in this paper, we are assuming competently trained pilots who are familiar with the aircraft and systems, although not necessarily familiar with a bird strike on both engines shortly after take-off.

3.4.1 Validity assessment

Once each of the three decision models were developed from the interview data, they were reviewed for their validity by an experienced Human Factors researcher and an experienced airline pilot. The Human Factors researcher reviewed the raw interview transcriptions and applied them independently to the three decision-making models. They were then reviewed by the airline pilot, with over 10 years of experience. The pilot was first introduced to the theories surrounding each of the models and how they capture decision making. The pilot then reviewed the models for their accuracy on pilot behaviour and thought processes. On the whole, the pilot found the models to be accurate in capturing pilot decision-making. Suggestions were made to the specific tasks and procedures in the Decision Ladders, with ‘Aviate, Navigate, Communicate’ tasks thought to encompass all high-level tasks and then the procedures relevant to each task being broken down in the following segment of the ladder. Furthermore, the pilot refined the situation shift that is noted in the situation assessment record within the RPDM, although no significant changes were required.

4. Results

This section will present the previous experience of the pilots that may influence their decision making, before presenting the three decision models generated from the interview data. It should be noted that the scenario presented to the pilots in the interviews was intended to be hypothetical and therefore the responses of the pilots could also only be hypothetical, based on their training, knowledge and experience. The processes presented are those stated to occur in the majority of cases.

4.1 Previous experience

None of the pilots interviewed had previously experienced a dual engine bird-strike or a dual engine failure while flying in the real-world. Two pilots had experienced a dual engine failure during simulator training. One pilot said that this would assist them if they were to face this event in the real-world as it would have significantly reduced the surprise and startle effect and therefore their response would be quicker. The other pilot had experienced a dual engine failure during cruise at 20,000ft in a training exercise. They stated that this would not assist them in the scenario under review as failure after take-off would involve more critical decision-making than the event they had experienced. Therefore, it is concluded that the pilots were largely inexperienced in the scenario under review.

All pilots did, however, state that they receive training for a single engine failure event on take-off as a part of their regular, standardised, training. During the training the cause of the engine failure is not noted as important as it focuses on how to manage the failure, regardless of it's cause. Therefore, whilst bird-strikes are not commonly found within training, pilots did state that a single engine failure event on take-off would assist them in responding to a possible single engine bird-strike event. While three pilots stated they had experienced a bird-strike to one engine in the real-world, none of these events were severe enough to damage the engine or affect the flight.

4.2 RPDM

The Situation Assessment Record (SAR; Klein et al, 1989) was applied to model the decision making from the RPDM perspective. The SAR identifies specific decision points along the event and the critical cues and goals that surround these points. An example is presented in Appendix B. The interview transcripts were reviewed to identify the different stages in the pilot's situational assessment. The SAR is shown in Table 1 and the application of the scenario to the RPDM is shown in Figure 4.

Table 1. Situational Assessment Record (SAR) of the bird-strike event

[Insert Table 1 here]

The application of recognition strategies was limited due to the pilot's inexperience of dual engine failures. Instead, they relied on experience of single engine failures on take-off and their knowledge of the QRH and checklists which outline the procedures for critical events. This assessment is shown in the first loop of the RPDM in Figure 4. Once they have established some recognition of a similar event, they move through to the process of assessing the situation. See Table 1 for details.

The pilot must determine how severe the engine damage is and if an engine shut down in required. Decision point 3 in the SAR in Table 1 states the pilot decides that at least one engine needs to be shut down. However, the flight-deck display does not give the pilot any information on the prioritisation or comparative damage to the engines. This has to be determined by the pilot's assessment of the engine parameters.

Phase 3 of the SAR in Table 1 states that the pilot would shut down one damaged engine and re-evaluate the safe flight of the aircraft. With two damaged engines, the pilot would then be aware that the remaining engine is still significantly damaged and has minimal thrust available. This is highlighted as a 'shift' in the situational assessment. At this point the pilot is faced with the highly unfamiliar and critical event of two failed engines at a low altitude shortly after take-off.

Due to the serial nature of the engine shut down procedure and the limited information on the comparative damage across the two engines, the pilots stated that they could be in a situation where they shut down an engine first that may have been able to provide more assistance than the second remaining engine. For example, one pilot stated "*what would be a bit of a travesty is if actually that engine was fine, but because of the limited amount of information, or the slightly ambiguous information that we have, if we decided not to re-light it then that's kind of a bit of a shame*" (P2). With two failed engines the pilots would need to consider all options for landing the aircraft as soon as possible, which would include non-airport locations, such as in the Hudson River incident. Pilots stated they would refer to the relevant QRH and ditching checklist.

Once the situation assessment is made, the RPDM in Figure 4 shows that mental simulation of the intended actions is generated by the pilot and then this is evaluated. Mental simulation involves determining if the intended landing site is feasible, given the perceived engine damage and environmental conditions. The RPDM states a serial process of considering options, however, there would be limited time for serial evaluation as the aircraft would lose altitude and begin to glide without thrust and power from an engine. There would be consideration of the available time, and if it is suitable to execute the emergency turn procedure, as identified in a pre-flight briefing. If not, additional serial evaluations would need to occur to identify a suitable alternative landing site.

[Figure 4 Here]

Figure 4. Recognition-Primed Decision model for dual engine bird-strike event.

4.3 Decision Ladder

The process outlined in Jenkins et al (2010) was followed, (see Appendix D). The complete Decision Ladder is shown in Figure 5.

The primary goal of the scenario was identified: ‘to land the aircraft safely as soon as possible with two damaged engines’. Physical environmental cues are the alert to the event. The ECAM/EICAS are also listed as possible alerts, as they have an alerting system when engine parameters are abnormal. The pilots’ response to an alert is a skill-based behaviour (Rasmussen, 1983), meaning that it is immediate and automatic – the pilots know they must respond. The observation of this alert is then noted in the Decision Ladder as a data processing activity. As Decision Ladders aim to capture the functioning of the system, and not just the individual, this can include the pilot’s processing of the alerting information but also the flight-deck technologies that are processing the information from the engine sensors to measure the impact of the bird-strike e.g. engine temperature and vibration. This then provides a ‘resultant state of knowledge’ within the Decision Ladder. The processing of the information and diagnosis is considered rule-based behaviour, with pilots using their stored rules to respond to alerts in the cockpit and try and identify what the situation is. The information presented is largely that on the flight deck itself and the engine parameters that the pilots must question to assist their diagnosis. The information shared between the two pilots is also used to inform the diagnosis which is the next data processing activity. Through this activity the system must determine the damage to both of the engines in order to select the best possible options. This requires interaction between the engine sensors, the engine parameter displays and the pilots expectations and knowledge of the situation.

At this stage, the environmental conditions are also considered to determine possible landing locations. This information is used to predict the consequences of possible scenarios and knowledge-based behaviour applies constraints and considers alternatives. As in the RPDM, the expectations of possible outcomes are simulated, except in the Decision Ladder they are not run in serial but concurrently. The different options are shown in Figure 5. The high-level system goal guides the option selection.

Two shunt shortcuts in Figure 5 capture how pilots stay up to date with the constantly updating situation by referring to information on the left-hand side of the ladder to inform their intended tasks and actions on the right side of the ladder. These tasks cover the ‘Aviate, Navigate, Communicate’ mantra that pilots are trained in.

Within this scenario no shortcuts were identified that allow decision-making to go from situation analysis to action taking (left to right). This was because this is a highly unfamiliar situation which occurs very infrequently in the real-world and is largely not covered in mandatory training. Therefore, while pilots may be experts in the domain, this scenario is largely outside of their expertise and they need to apply knowledge-based behaviour to fully understand the extent of the damage, all possible options available to them and their predicted consequences.

[Figure 5 Here]

Figure 5. Decision Ladder of the dual engine bird-strike scenario

4.4 PCM

Following the approach used by Plant and Stanton (2016), the transcripts were coded to the ‘Schema Action World’ taxonomy (Plant & Stanton, 2016) to generate an aggregated PCM. The taxonomy includes 11 World classifications, 6 Schema classifications and 11 Action classifications, deemed to be fully encompassing of all areas of the PCM (Plant & Stanton 2016). The full SAW taxonomy is listed in Appendix C. Each of the processes in the PCM were then coded to the different phases of the incident; Pre-incident, Onset of the problem, Immediate actions, Decision-making, Subsequent actions, Incident containment (Plant & Stanton, 2012; 2014).

[Figure 6 Here]

Figure 6. Perceptual Cycle Model representing the dual engine bird-strike event

Figure 6 shows the onset of the incident in the ‘world’, from the physical cues of the bird-strike itself (Step 1 in Figure 6). This would be subject to a startle and/or surprise effect, reflecting an insufficient schema (2) as pilots do not initially know what is happening due to unanticipated and unusual nature of the event. The pilot’s initial priority to fly the aircraft (3) is captured as the first ‘action’ in the PCM and it is still considered to be within the initial onset of the incident as the pilot is not initially making any decisions.

Pilots reported that the pilot flying would deliver max thrust to both engines to determine how much thrust they had available, as this is key to remaining airborne. If the autopilot is active, then the pilot would keep it active to reduce workload. On some occasions the autopilot may deactivate and require the pilot to regain manual control of the aircraft. The pilots would then monitor the engine displays (4) to assess what has happened and this marks the next phase of the incident, 'immediate response'. The PCM represents the engine displays as information within the world (5) that present the damage sustained from the bird-strike. This information is then processed by the pilots' schema (6). This was coded as an analogical schema as pilots use their prior knowledge for the dial reading to interpret the state of the engine. From this they can generate expectations about what has happened and what further actions may be required. The situation would be assessed as highly critical, therefore the captain would take over flying the aircraft (7) and they would then initiate the emergency turn procedure (8). As stated previously, this is a key aspect of the emergency response that pilots are trained to perform. Immediately after initiating the turn, pilots would make a Mayday call to ATC to inform them of the emergency situation (9). Following this, pilots would then need to further determine the severity of the situation and what actions they would need to take to maintain safe flight (10), this is where the 'decision-making' phase begins.

The engine parameters are presented on the flight deck within the 'world' component (11). The following schema element requires assessing the individual engine parameter displays to understand the extent of the damage to both engines (12). Pilots stated that information on the engine temperature and vibrations would inform them if they need to shut an engine down. This uses declarative schema, their knowledge of what the parameters are indicating. This is informed by their training (13). The pilots had limited experience of a dual engine failure on take-off event and reported that they would rely on the QRH and checklists to inform their knowledge on what actions to take. The 'subsequent actions' phase is therefore started as the checklists guide the following required actions. The process of running through the checklist is shown in the 'Action' component (14a) and the information on the checklist itself is evident in the 'world' (14b). The guidance in these checklists will lead pilots to land the aircraft as soon as possible in the best possible location. This requires their declarative schema and knowledge of the local environment to determine where the best possible location may be (15). If the pilots have taken off from a familiar airport, they may have knowledge of the area or they may be relying on navigation displays or simply looking out the window. Pilots stated that they would action their company specific decision tool (e.g. T-DODAR), which would help structure what their next actions are (16). This leads to the 'incident containment' phase as the decision tool aims to assist pilots in managing and containing events. The scenario finishes with the landing of the aircraft which requires the pilot to fly the aircraft (17) and monitor the environment surrounding them in the world (18).

5. Discussion

The purpose of modelling decision-making is to understand where it can be improved or guided using decision aids (Simpson, 2001; Mosier & Skitka, 1997; Dorneich et al, 2017; Mosier & Manzey, 2019; Parnell et al, 2019; Banks et al, 2020a). Three different decision models have been applied to pilots' responses to a dual engine failure of take-off event. The different decision models provide some complimentary and some varying insights into how pilot decision-making can be supported in the event of a dual engine failure on take-off. A summary of the differences are shown in Table 2. The implications that this has for the development of a decision aid are discussed.

Table 2. Summary of key differences across the decision models

[Insert Table 2 here]

The RPDM highlights the importance of recognition in the alerts that pilots are given to quickly diagnose the situation. As recognition is the initial step in the RPDM process, recognition for the exact nature of the problem needs to come at the start of the decision-making process. The serial nature of option generation and selection further highlights the need to recognise the severity of the event from the time of the alert. Figure 7 shows how a decision aid could be applied within the RPDM as a cue within the situational assessment. A decision aid that could provide the cue that both engines were damaged and clearly show the extent of the damage would enable the pilot to have accurate expectations at an early stage in the decision-making process. This would limit multiple, serial cycles of the model, which is key in a time critical event. Furthermore, a display that utilises principals that are familiar and recognisable as an engine failure are recommended.

[Insert Figure 7 Here]

Figure 7. RPDM showing where the decision aid could assist pilots in a dual engine failure on take-off event.

The RPDM only requires 'good enough' (Simon, 1955) decisions to be made, rather than optimal ones (Klein & Calderwood, 1996). Yet, the aviation domain upholds stringent decision-making practices to ensure that its pilots act in a justifiable manner, in-keeping with standards (Kaempf & Klein, 1994). For example, in the case of the Hudson incident the FAA undertook a largescale investigation into the actions of the pilots who then had to defend themselves in a court of judgement. Participants also commented that they were aware that all their decisions had to be justified. Participant 6 stated "*If you can turn around and say you followed the SOPs…and you're allowed to deviate from the standard operating procedures only for reasons of safety…But[only] if you can stand up and justify your actions in court*". Application of the RPDM must therefore consider the importance of the decision and its implications. In emergency situations, such as the one studied here, safety is the priority and other factors are often easily traded off. For example, the pilots said that the companies preferred choice of landing sites, or costs to the company would not factor into their decision making due to the critical nature of this error. The RPDM therefore captures how the assessment and goals of the pilots prioritise the passenger's safety. If further detail in the decision making is required, then the RPDM may be of little use as it cannot provide more guidance on fine tuning systems to optimise outcomes.

In comparison to the RPDM the PCM and Decision Ladder dictate analogical reasoning with multiple options considered in parallel. Therefore, they require information to be accurate and up-to-date for options to be compared against one another. The RPDM is more concerned with contrasting the experienced event with previous experience to inform action and is less adaptive to the situation in hand. Therefore, when designing systems that require decisions in dynamic environment that are subject to variable pressures the PCM and Decision Ladder are better options.

The decision models can also be compared on how they capture the decision maker. The RPDM is primarily focused on the cognitive processing of the individual decision maker; their familiarity with the situation, generation of expectations and mental simulation of possible actions. Decision Ladders focus on understanding the characteristics of the work domain and the actions that are conducted within it rather than the individuals themselves (Naikar, 2010). They make no distinction between automated or human operated tasks (Jenkins et al, 2010). A decision aid can therefore be viewed as an automated actor within the system to replace human operator tasks. A decision aid could act as the expert within this scenario and could assist the pilot in using rule-based behaviour to short-cut the decision-making process, making it more efficient (Banks et al, 2020b). Figure 8 shows how a decision aid could be included within the Decision Ladder to provide a shortcut, from knowledge of the system state to the tasks required to manage the issue. It does so by providing information on the target state. This leap across the system represents the replacement of knowledge-based behaviour with an automated system, as the decision aid can understand what the options are by assessing the state of the system (e.g., both engines are severely damaged and the aircraft needs to be landed as soon as possible).

[Insert Figure 8 Here]

Figure 8. Decision Ladder showing where the decision aid could assist in managing a dual engine failure on take-off

Not only is the decision ladder able to provide insight into autonomous agents within the decision process, it can also suggest how these autonomous agents should function. The questions and responses detailed in the knowledge-based behaviour category on the ladder act as requirements for the information that the decision aid should provide. The pilot is removed from the process of generating different options, predicting consequences, and determining the target state. Furthermore, it could override the need to reference a traditional QRH. The current QRH and checklists were found to be inappropriate for events such as a dual engine failure by the NTSB (2010) report of the Hudson River incident. Instead, a system that could monitor the continual state of the engine, would be able to inform the pilot of the state of damage to both engines. The decision aid could then inform pilots of the tasks required and time frames for them to be completed in e.g. to relight the engines or shut them down, and maintain the safety of the flight, action emergency turn procedure etc. The Decision Ladder is useful here in identifying the role that a decision aid could have within the wider system, as the basis of Decision Ladders is to identify the work required by all actors in a system (Jenkins et al, 2010).

The PCM also considers the broader system in which decisions occur, but it considers this in relation to the schemata of the individual and how the world, and actions within it, influence the cognitive processing of the individual. Schemata are anticipatory and foresee information in the environment to direct appropriate action. Knowledge structures comprising the schemata can also be updated to guide the exploration and interpretation of future information. The RPDM focuses on the individual's perspective, but it does not account for the interactional nature of the environment and the impact it has on shaping behaviour (Lipshitz & Shail, 1997; Plant & Stanton, 2014). There are no feedback or feed-forward loops to capture how an individual communicates with their environment (Plant & Stanton, 2014). This is also evident in the starting point of the decision-making. Both the PCM and Decision Ladder start with the initial event in the external environment and how it first presents itself to the decision maker, e.g. a physical cue (bang/vibration/smell) and/or the engine instruments on the flight deck. Conversely, the RPDM starts from the point at which the event is experienced by the decision-maker and proceeds to assess their cognitive processing of this experience.

The interactional nature of the individual with the environment within the PCM means that it requires information to be accurate and up to date. Real-time information on the state of the engine would assist in reducing the ambiguity in the decision-making process. The introduction of a decision assistant that could provide such information is shown in Figure 9 as assisting at both the immediate response stage and the decision-making stage. An aid that could provide real time information on the state of damage to the engine itself would inform the pilots initial expectations of the event (steps 5 to 6 on Figure 9) and guide the captains' response.

As option generation occurs in parallel, referring back to the information on the engine state throughout the decision-making process in the link between step 11 and 12, would provide a more accurate representation of the event in the pilots' schema and therefore an improved chance of an accurate diagnosis in the following stages of decision making and the subsequent action. This varies from the RPDM which suggests the importance of an aid to help recognise the situation at the very beginning of the process due its serial decision-making process. Furthermore, an awareness of the changing situation with updated information would also allow for more optimal decisions, rather than satisfactory ones. Applying the PCM can therefore assist in understanding how a decision aid will interact with the cognitive processing of the pilot and the wider environment, as this changes across the decision event.

[Insert Figure 9 Here]

Figure 9. PCM of the dual engine failure scenario showing where the decision aid could provide assistance to the pilot on the flight deck.

As depicted in Table 2, the RPDM and Decision Ladders are divergent in their approaches, yet the PCM falls somewhere in the middle of the two, as it can account for the cognitive processing of the individual and the interaction of the wider systemic elements. The ability to account for the wider context has enabled the PCM and Decision Ladders to be utilised for exploring decision making with autonomous agents (Roth et al, 2019; Banks et al, 2018; Revell et al, 2021). To enable successful human-autonomous interactions, models that incorporate autonomous agents and their interactions with the environment will be necessary. The RPDM may be somewhat outdated in this respect, it relies on the recognition for events based on past experiences, yet many of the experiences that autonomous agent will bring will be novel and there will be a steep learning curve to understand how their decision-making processes relate to our own, if they do at all.

The findings from this research suggest that models that can account for the role of the environment will be able to provide more detailed information on the systems dynamic requirements. They can help to provide updates and real-time feedback. The Decision Ladder approach is particularly useful in scoping out the information that a decision assistant needs to provide in order to replace human knowledge. Therefore, this method is advocated for those considering the design of an automated decision aid. The PCM is, however, particularly useful at presenting how a decision aid will be integrated within a certain scenario and how it will shape the experience of the individual, as well and their interactions with the environment. Therefore, this method is advocated in the review of a decision aid after its initial design to understand how it may interact within a system. This could allow any unforeseen and unintentional interactions to be reviewed early on in the design process.

Conversely, the RPDM shows value in the initial alerting of the need for the decision and the interpretation of the situation but not how this can relate back to the environment. Its use may therefore be more limited to the design of alerts once systems have failed, in order to inform individuals of the situation and guide their response.

Table 3 summarises the different insights into future measures from the different models in relation to the dual-engine failure scenario.

Table 3. Summary of the decision model recommendations

[Insert Table 3 Here]

5.1 Limitations and future work

Utilising the CDM approach to obtain verbal reports and develop decision models has led to the development of three different decision-making approaches. However, when applying verbal reports caution must be applied as they rely on memory and hypothetical reasoning that may mean that the models don't capture all aspects of real-world decision-making (Klein & Armstrong, 2005). Context plays a large role in decision making and this was not able to be fully captured within the interviews we conducted. Factors such as time-pressure, startle and surprise can have a significant impact on pilot decision making within critical situations (Landman et al, 2017). Future work seeks to validate the decision-making processes captured here within a flight simulator environment to understand how accurate the pilots reports were. The simulator will also be designed to incorporate decision aids that will be designed with input from the decision models presented here.

6. Conclusion

Applying three different naturalistic decision models to the scenario of a dual engine failure on take-off has obtained insight into pilot decision-making and how this could be better supported with a future decision aid. It has shown the similarities and differences across the decision-making models. The RPDM focuses predominantly on the decision as experienced by the decision-maker. Decision Ladders focus on the processes irrespective of the actor. The PCM incorporates the cognitive processes of the decision maker and the other information in the world that influences decision-making. Applying these three different models has enhanced the understanding of the scenario with regard to these different perspectives. Some of the limitations of solely applying the RPDM were revealed with limited information on the interaction of other elements in the situation outside of the pilots' head and their experience of the event. The application of all three of the models was able to demonstrate where a decision aid could provide information on the state of the engine, to support better decision-making. This assumption needs to be tested empirically, which is an important goal for future research.

References

Asmayawati, S., & Nixon, J. (2020). Modelling and supporting flight crew decision-making during aircraft engine malfunctions: developing design recommendations from cognitive work analysis. *Applied Ergonomics, 82*, 102953.

Banks, V.A., Allison, C.K., Plant, K.L., Parnell, K.J., and Stanton, N.A. (2020a). Using SWARM to generate design requirements for new systems on the Open Flight Deck. *Human Factors and Ergonomics in Manufacturing & Service Industries.* Online Version https://doi.org/10.1002/hfm.20869

Banks, V. A., Plant, K. L., & Stanton, N. A. (2018). Driver error or designer error: Using the Perceptual Cycle Model to explore the circumstances surrounding the fatal Tesla crash on 7th May 2016. *Safety Science, 108*, 278-285.

Banks, V. A., Plant, K. L., & Stanton, N. A. (2020b). Leaps and Shunts: Designing pilot decision aids on the flight deck using Rasmussen's ladders. Proceedings from *Contemporary Ergonomics and Human Factors Conference 2020.* https://publications.ergonomics.org.uk/publications/leaps-and-shunts-designing-pilot-decision-aids-on-the-flight-deck-using-rasmussens-ladders.html

Bartlett, F. C. (1932). *Remembering: A study in experimental and social psychology*. Cambridge University Press.

Charter Institute for Ergonomics and Human Factors (2020) The Human Dimension in Tomorrows Aviation System [White Paper] https://www.ergonomics.org.uk/common/Uploaded%20files/Publications/CIEHF-Future-of-Aviation-White-Paper.pdf

Dorneich, M. C., Dudley, R., Letsu-Dake, E., Rogers, W., Whitlow, S. D., Dillard, M. C., & Nelson, E. (2017). Interaction of automation visibility and information quality in flight deck information automation. IEEE Transactions on Human-Machine Systems, 47(6), 915-926.

Gore, J., Ward, P., Conway, G.E., Ormerod, T. C., Wong, B. L. W. & Stanton, N. A. (2018) Naturalistic decision making: navigating uncertainty in complex sociotechnical work. Cognition, Technology and Work, 20, 521–527.

Harris, D. and Stanton, N.A. (2010) Aviation as a system of systems. Ergonomics, 53, (2), 145-148.

Hu, Y., Li, R., & Zhang, Y. (2018). Predicting pilot behavior during midair encounters using recognition primed decision model. *Information Sciences*, 422, 377-395.

Jenkins, D. P., Stanton, N. A., Salmon, P. M., Walker, G. H., & Rafferty, L. (2010). Using the decision-ladder to add a formative element to naturalistic decision-making research. *International Journal of Human–Computer Interaction, 26*(2-3), 132-146.

Klein, G. A., Orasanu, J., Calderwood, R., & Zsambok, C. E. (1993). *Decision making in action: Models and methods*. Norwood, NJ: Ablex Publishing Corporation.

Klein, G. A. (1989). Recognition-primed decisions. In W. B. Rouse (Ed.*), Advances in man-machine systems research* (Vol. 5, pp. 47–92). Greenwich, CT: JAI Press.

Klein, G. A., Calderwood, R., & Macgregor, D. (1989). Critical decision method for eliciting knowledge. *IEEE Transactions on Systems, Man, and Cybernetics, 19*(3), 462-472.

Klein, G. A. (2008). Naturalistic decision making. *Human Factors, 50*(3), 456-460.

Klein, G. A., & Calderwood, R. (1996). *Investigations of Naturalistic Decision Making and the Recognition-Primed Decision Model*. Klein Associates Inc. Yellow springs, Ohio, USA.

Landman, A., Groen, E. L., Van Paassen, M. M., Bronkhorst, A. W., & Mulder, M. (2017). Dealing with unexpected events on the flight deck: a conceptual model of startle and surprise*. Human Factors, 59*(8), 1161-1172.

Lintern, G. (2010). A comparison of the decision ladder and the recognition-primed decision model. *Journal of Cognitive Engineering and Decision Making, 4*(4), 304-327.

Lipshitz, R. (1993). Converging themes in the study of decision making in realistic settings. In G. A. Klein, J. Orasanu, R. Calderwood, & C. E. Zsambok (Eds.), *Decision making in action: Models and methods* (pp. 103–137). Norwood, NJ: Ablex.

Lipshitz, R. & Shaul S.B. (1997) Schemata and mental models in recognition-primed decision making In. Zsambok C.E, & Klein G. (Eds.), *Naturalistic Decision Making*, Lawrence Erlbaum, Mahwah, NJ, pp. 60-72

Mosier, K. L., & Manzey, D. (2019). Humans and Automated Decision Aids: A Match. In (eds) Mouloua M. & Hancock P.A., *Human Performance in Automated and Autonomous Systems: Current Theory and Methods,* CRC Press, Chicago p19-41.

Mosier, K. L., & Skitka, L. J. (1996). Human Decision Makers and Automated Decision Aids: Made for Each Other?. In (eds) Parasuraman R. & Mouloua M. *Automation and Human Performance: Theory and applications New York*, NY: CRC Press. p. 120

McIlroy, R. C., & Stanton, N. A. (2015). A decision ladder analysis of eco-driving: the first step towards fuel-efficient driving behaviour. *Ergonomics, 58*(6), 866-882.

National Transportation Safety Board (2010). *Loss of Thrust in Both Engines After Encountering a Flock of Birds and Subsequent Ditching on the Hudson River, US Airways Flight 1549 Airbus A320-214, N106US, Weehawken, New Jersey, January 15, 2009*. Washington D.C. Online source: https://www.ntsb.gov/investigations/AccidentReports/Reports/AAR1003.pdf (Accessed 08/06/2020)

Naikar, N. (2010). *A Comparison of the Decision Ladder Template and the Recognition-Primed Decision Model*. DSTO-TR-2397. Air Operations Division. Defence Science and Technology Organisation. Australian Government Department of Defence. Victoria, Australia

Neisser, U. (1976) *Cognition and Reality*. San Francisco: W. H. Freeman.

Neville, T. J., Salmon, P. M., & Read, G. J. (2017). Analysis of in-game communication as an indicator of recognition primed decision making in elite Australian rules football umpires. *Journal of Cognitive Engineering and Decision Making, 11*(1), 81-96.

Parnell, K. J., Banks, V. A., Plant, K. L., Griffin, T. G. C., Beecroft, P. and Stanton, N. A. (2019) Predicting design induced error on the flight deck: An aircraft engine oil leak scenario. *Human Factors*, online first: https://doi.org/10.1177/0018720819872900.

Plant, K. L., & Stanton, N. A. (2012). Why did the pilots shut down the wrong engine? Explaining errors in context using Schema Theory and the Perceptual Cycle Model. *Safety Science, 50*(2), 300-315

Plant, K. L., & Stanton, N. A. (2016). The development of the Schema World Action Research Method (SWARM) for the elicitation of perceptual cycle data. *Theoretical Issues in Ergonomics Science, 17*(4), 376-401.

Plant, K. L., & Stanton, N. A. (2014). The process of processing: Exploring the validity of Neisser's perceptual cycle with accounts from critical decision-making in the cockpit. *Ergonomics, 58*, 909-923.

Plant, K. L., & Stanton, N. A. (2015). The process of processing: exploring the validity of Neisser's perceptual cycle model with accounts from critical decision-making in the cockpit. *Ergonomics, 58*(6), 909-923.

Rasmussen, J.1974. *The Human Data Processor as a System Component. Bits and Pieces of a Model*. Riso-M-1722, Roskilde, Denmark: Risø National Laboratory.

Rasmussen, J. (1983). Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. *IEEE transactions on systems, man, and cybernetics*, (3), 257-266.

Revell, Kirsten MA, Joy Richardson, Pat Langdon, Mike Bradley, Ioannis Politis, Simon Thompson, Lee Skrypchuck, Jim O'Donoghue, Alex Mouzakitis, and Neville A. Stanton. "Breaking the cycle of frustration: Applying Neisser's Perceptual Cycle Model to drivers of semi-autonomous vehicles." *Applied Ergonomics, 85* (2020): 103037.

Roth, E. M., Sushereba, C., Militello, L. G., Diiulio, J., & Ernst, K. (2019). Function allocation considerations in the era of human autonomy teaming. *Journal of Cognitive Engineering and Decision Making, 13*(4), 199-220.

Salas, E., Maurino, D., & Curtis, M. (2010). *Human Factors in Aviation* (2nd Ed.). Academic Press. San Diego.

Simon, H. A. (1955). A Behavioral Model of Rational Choice. *Quarterly Journal of Economics, 69*, 99–118.

Simpson, P. A. (2001). Naturalistic decision making in aviation environments. Defence Science and Technology Organisation Victoria (Australia). Air Operations Division, Aeronautical and Maritime Research Lab. DSTO-GD-0279.

Stanton, N. A., Li, W-C. and Harris, D. (2019) Ergonomics and Human Factors in Aviation, Ergonomics, 62 (2), 131-137.

Stanton, N. A., Rafferty, L. A., Salmon, P. M., Revell, K. M. A., McMaster, R., Caird-Daley, A. and Cooper-Chapman, C. (2010) Distributed decision making in multi-helicopter teams: case study of mission planning and execution from a non-combatant evacuation operation training scenario. Journal of Cognitive Engineering and Decision Making, 4 (4), 328–353.

Stanton N. A., Salmon P. M., Walker G. H. and Jenkins D. P. (2017) Cognitive Work Analysis: Applications, Extensions and Future Directions. CRC Press: Boca Raton, USA.

Stanton, N. A. and Walker, G. H. (2011) Exploring the psychological factors involved in the Ladbroke Grove rail accident. Accident Analysis & Prevention, 43 (3), 1117-1127.

Vicente, K. J., & Rasmussen, J. (1992). Ecological interface design: Theoretical foundations. *IEEE Transactions on systems, man, and cybernetics, 22*(4), 589-606.

Vidulich, M. A., Wickens, C. D., Tsang, P. S., & Flach, J. M. (2010). Information processing in aviation. In *Human factors in aviation* (pp. 175-215). Academic Press.Chicago

Yang, Q., Sun, X., Liu, X., & Wang, J. (2020). Multi-Agent Simulation of Individuals' Escape in the Urban Rainstorm Context Based on Dynamic Recognition-Primed Decision Model. *Water, 12*(4), 1190.

Tables

Table 1. Situational Assessment Record (SAR) of the bird-strike event

SA – 1	
Cues/knowledge	Hear, feel, see or smell birds hit the engine. Engine instrumentation, N1/N2, high vibration indication and/or high temperature
Expectations	Potential dual engine damage, one engine may give some thrust, Risk to flight safety, plane cannot maintain altitude with reduced thrust
Goals	Maintain the flight of the aircraft (manual or with autopilot) to assess available thrust Decision point 1: Activate autopilot (if not already engaged) Decision point 2: Cross confirm flight and engine metrics with co-pilot
SA – 2 (Elaboration)	
Cues/knowledge	Engine indicators show engine parameters, ECAM message, available thrust, confirmation from co-pilot on engine damage, QRH/checklists for engine shut down
Expectations	At least one engine is severely damaged, engine may be on fire, engine(s) may need to be shut down and isolated
Goals	Determine if the damaged engine(s) need to be shut down, maintain enough altitude to reach a suitable landing position Decision point 3: Determine that engine damage is severe and at least one engine needs to be shut down and isolated
SA – 3 (Elaboration)	
Cues/knowledge	ECAM message, engine indicators show engine parameters, QRH/checklist for engine shut-down
Expectations	Shut-down engine to isolate it and prevent further damage. Shut-down the most damaged engine
Goals	Maintain enough thrust to return and land at departure airport Decision point 4: Return to departure airport
SA – 4 (Shift)	
Cues/knowledge	Second engine may need to be shut down – ECAM and engine indicators
Expectations	Both engines are severely damaged and cannot generate thrust from the remaining engine
Goals	Shut down both engines; action emergency turn procedure; identify best available landing position Decision point 5 – Land the aircraft in best possible location with two damaged engines
SA – 5 (Elaboration)	
Cues/knowledge	Pre-flight briefing identified the emergency turn procedure, Navigation display and view outside identify available landing positions, QRH checklist for aircraft ditching
Expectations	Need to perform an emergency turn, may need to 'ditch' the aircraft
Goals	Perform emergency turn procedure; land aircraft safely

Table 2. Summary of key differences across the decision models

Aspect of decision-making	RPDM	PCM	Decision Ladder
Decision must be justifiable	No *Non-optimum decision making*	Yes	Yes
Options are generated in parallel and compared	No *Options considered in serial*	Yes	Yes
Focuses on the cognitive processing of an individual decision maker	Yes	Yes	No *Focuses on tasks in the system*
Accounts for previous experience of the decision-maker	Yes	Yes	No *Focuses on tasks in the system*
Accounts for the interaction of other actors in the decision-making process	No *Focuses on the individual*	Yes	Yes
Starts with initial event in the environment	No *Starts with the experience of the event by the individual*	Yes	Yes

Table 3. Summary of the decision model recommendations

Decision Model	Recommendation
RPDM	• Allow early recognition of the full severity of the event i.e. cues to the damage on both engines at the same time to give accurate expectations of future actions • Present information in a familiar format so that they can recognise it as a dual-engine engine failure
PCM	• Reduce ambiguity in the state of damage to the engine to update the pilots schema • Provide real-time, accurate data that can be referred to throughout the decision-making process
Decision Ladder	• Provide information in current system state and target system state by processing the options available and presenting the best course of action for pilots to action • Short-cut the decision-making and limit the need for knowledge-based behaviour from the pilot

Figure legends

Figure 1. The Recognition-Primed Decision Model (adapted from Klein et al, 1993)

Figure 2. Decision Ladder framework template (*adapted from Jenkins et al, 2010*)

Figure 3. Representation of the PCM adapted from Neisser (1976)

Figure 4. Recognition-Primed Decision model for dual engine bird-strike event.

Figure 5. Decision Ladder of the dual engine bird-strike scenario

Figure 6. Perceptual Cycle Model representing the dual engine bird-strike event

Figure 7. RPDM showing where the decision aid could provide assistance to the process of managing a dual engine failure on take-off.

Figure 8. Decision Ladder showing where the decision aid could provide assistance to the process of managing a dual engine failure on take-off

Figure 9. PCM of the dual engine failure scenario showing where the decision aid could provide assistance to the pilot on the flight deck

Appendices

Appendix A - Interview prompts

Part 1 – Scenario

Please read through the following scenario:

You are on a twin-engine aircraft during its initial climb (~ 2800 feet). A flock of birds strike ***both*** *engines. You must…*

  - *Determine the criticality of the situation (e.g., state of each engine)*
  - *Take appropriate action*

Please state your initial thoughts on this scenario.

Part 2 – Semi-structured Interview Probes

Cues

- What aspect of the flight deck would you be monitoring?
  - What information would you require?
- Would this information influence you?
  - If so how?

Goals/Actions

- What physical actions would you take?
- What navigational actions would you take?
- What inputs/actions would you make that would have a direct effect on the technological systems in the flight deck?
- Would your actions be standard/typical for the situation? If yes/no why?
- Would you follow a checklist of procedures (memorised or physical)?
  - If so, what?

Knowledge

- What information would you use to inform physical actions?
- Would you alter your physical actions based on new information becoming available?
  - *If so how?*
  - Would there be actions that you may want to perform but wouldn't?
- What information would you use to inform any navigation decisions?
- Would you require any information about your location?
  - If so what?
- Would you require any information about your natural environment?
  - If so what and why?
  - Where would you get this information?
  - Would you be monitoring anything in the natural environment?
    - If so how would this effect your actions?

Analogues

- Has the situation(s) happened to you before?
    - If not have you heard about this scenario happening before?

Experience

- Have you had any training that would influence your response to the scenario(s)?
    - If so, how would it influence you and/or your expectations?
- Would any anticipated consequences influence your decisions?
- Would you feel comfortable managing this scenario(s)?
- What is the key factual information you would rely on in this situation(s)?

Situation Assessment

- How would you assess the situation?
- How would you evaluate and interpret the information available to you?
- What could you conclude based on your situation awareness?
- Would any psychical cues be available to you? *(e.g. vibration/smell)*
- How severe is this problem?
- What information would you uses to assess the severity?
- How does the severity influence your response?
- Would you take any action to specifically reduce the severity of the situation?
    - If yes, what?
    - Would you be concerned of the status of the aircraft?

Communicate

- Would you communicate with anyone?
    - If so who and what about?
- Would you require information from others?
    - How would you acquire it and from who?
- Would you share information any other way?
- Would any communications influence you?
    - If so how?

Hypotheticals

- Would you be concerned about the reliability/relevance of the information available to you?
    - What inputs would you make into the technological system in the flight deck?

Context

- How would the operational context influence you?
- Would you take any operational actions?

Crew

- What would your crew members be doing?
- How would your crew members influence your behaviour/decision-making?

Appendix B –Situation Assessment Record (SAR) Analysis

SAR adapted from Klein et al, (1989) describing how decision making is analysed when applying the RPDM approach to develop the SAR.

SA – 1	Initial assessment of the situation
Cues/knowledge	Information and knowledge that the decision maker uses to inform their situational assessment
Expectations	The decision makers expectations about the situation based on the information and knowledge they have
Goals	The resulting goal to manage the situation based on their expectations Decision Point: Key decision that needs to be made in review of expectations and desired goals
SA – 2 (Elaboration)	Update of their situational awareness based on new information and cues
Cues/knowledge	New information and knowledge that updates the situational awareness
Expectations	Updated expectations based on this new information
Goals	Updated goals in accordance with any new expectations about the situation Decision Point: Updated or new key decision that needs to be made in review of new expectations and desired goals
SA – 4 (Shift).	Possible shift in the situational assessment based on additional information/events
Cues/knowledge	New knowledge and information that changes the situational assessment
Expectations	Renewed expectations based on the change in situation assessment
Goals	Renewed goals based on the new expectations about the situation. Decision Point: A shift in the decisions based on the shift in the situational assessment and resulting change in goal.

Appendix C – SAW Taxonomy

Schema Action World Taxonomy as defined in Plant and Stanton (2017)

Taxonomy subtype	**Description**
	Schema Subtypes
Vicarious past experience	Statements relating to experiencing something in the imagination through the description by another person (e.g. hearing a colleague recall an incident they were involved with) or documentation (e.g. reading about a certain event in an industry magazine or incident/accident report)
Direct past experience	Statements relating to direct personal experience of similar events or situations in the past. This covers events experienced in live, operational contexts as opposed to those experienced through training.
Trained past experience	Statements relating to knowledge developed by direct personal experience of a specific task, event or situation, experienced within the confines of a training scenario (e.g. ground school training, simulator training or training sorties) Statements relating to a schema that manifests as a descriptive knowledge of facts, usually as a product of the world information available
Declarative schema	Statements relating to a schema that manifests as a descriptive knowledge of facts, usually as a product of the world information available
Analogical schema	Statements relating to comparisons between things for the purpose of explanation and clarification. Typically these analogies will be structural analogies of physical objects or states of affairs in the world (akin to mental map or mental model)
Insufficient schema	Statements relating to inadequate or lacking knowledge, i.e. a schema is not developed for a certain situation
	Action Subtypes
Aviate	Statements relating to direct manipulation (handling) of flight controls in order that the aircraft can be flown and safety is maintained
Navigate	Statements relating to the process of accurately ascertaining position and planning and following a route or desired course
Communicate	Statements relating to the sharing or exchange of information
System management	Statements relating to the processes of making an input into technological systems in order that the interaction or manipulation has an explicit output
System monitoring	Statements relating to looking at (observing, checking) displays to gain an understanding of the situation
Environment monitoring	Statements relating to observing or checking the internal or external physical environment in order to establish the current state-of-affairs
Concurrent diagnostic action	Statements relating to the process of determining, or attempting to determine, the cause or nature of a problem by examining the available information at the time the incident is occurring
Decision action	Statements relating to a conclusion or resolution that is reached after considering the available information
Situation assessment	Statements relating to actions that relate to the evaluation and interpretation of available information
Non-action	Statements relating to actions that were not performed, either because the situation didn't warrant a particular action or because equipment faults did not allow a particular action to be performed or because the pilot made an error or omission.
Standard Operating Procedure	Statements relating to following the prescribed procedure that ought to be routinely followed in a given situation

World Subtypes	
Natural environmental conditions	Statements about natural environmental conditions (e.g. weather, light, temperature, noise)
Technological conditions	Statements relating to the state of technological artefacts (e.g. with regards to appearance and working order)
Communicated information	Statements relating to information available to the pilot from other people (e.g. other crew members, ATC, coastguard etc.)
Location	Statements relating to particular places or positions
Artefacts	Statements discussing physical objects, including written information, symbols, diagrams or equipment
Display indications	Statements relating to the information elicited from the physical artefacts
Operational context	Statements relating to the routine functions or activities of the organisation (e.g. Search and Rescue, Police search, military training etc.). This can include statements about the importance of being serviceable for the operational context or crew familiarity with the aircraft and how this effects decision making.
Aircraft status	Statements relating to the current status of the aircraft's integrity or performance (e.g. how good or bad it is flying, the current configuration of the aircraft, autopilot activation etc.)
Severity of problem	Statements relating to how bad (or otherwise) the critical incident is
Physical cues	Statements relating to external cues that provide information of conditions
Absent information	Statements relating to information that was missing, not present or lacking.

Appendix D - Decision Ladder Data Analysis

Table of the stages in developing Decision Ladders, adapted by Jenkins et al (2010).

Stage	Description
Stage 1- Determine the goal	Determine the structure of the goal of the system to frame the decision ladder. The goal was placed in the format “to (insert goal) (insert constraints) as stated in the Jenkins et al (2010) method.
Stage 2- Alert	The participants chronological reporting of the event detailed how they would first be alerted to the event. This is the aspect of the event that draws the user’s attention to possible incident. In this scenario it is the events immediately following the bird-strike, including the physical cues, visuals and actual alerts on the flight deck.
Stage 3- Information	This is information that the pilots use to identify what the issue was they were facing. This included the displays and indicators of engine damage that they could access on the flight deck.
Stage 4- System State	This is the perceived understanding of the system based upon the information available and its interpretation. It is the combined information from different available sources which are fused together. This refers to the assessment pilots make on the information they receive from the flight deck and other sources.
Stage 5- Options	The options present the different opportunities to change the system state to attain the higher-level goal. The system state determines the number and possibilities of the options.
Stage 6- Chosen Goal	The chosen goal is deemed by Jenkins et al (2010) to be determined by selecting the constraints with the highest priority. It is the one that will lead to the largest safety benefits.
Stage 7- Target State	The target states match the options available. Once an option has been selected it then becomes a target state to be attained. The target states are rephrased from the options as proposed in Jenkins et al, 2010.
Stage 8- Task	The tasks are the actions that are required to achieve the target state and maintain the overall goal.
Stage 9- Procedure	The procedures are the actions that comprise the tasks listed above.
Stage 10- Shortcuts	This is an additional stage not included within Jenkins et al (2010) initial methodology but are a key feature of the model (Banks et al, 2020). Shortcuts identify the advanced processing that occurs in familiar situations and with experienced actors that allows links to make across the two sides of the ladder.