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Decision Ladder application analyzing a helicopter emergency

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Abstract

This article aimed to analyze how the decision ladder can be used to evaluate emergencies in aircraft, assist in identifying relevant information, and even improve existing procedures. A case study was conducted based on a real occurrence of an emergency light indicating the presence of metallic particles in a Black Hawk helicopter transmission oil flying in the Amazonian scenario. Based on the decision ladder methodology, it was verified that the occurrence analyzed was not correctly addressed in the flight manual, and there would be a need for the inclusion of a new emergency procedure in the flight manual, which would allow the crew to separate a situation of major risk from one of minor risk.

Keywords: Decision Ladder. Flight crew decision-making. Flight safety. Flight manual.

1. Introduction

1.1 Case study

During a ferry flight of a H-60L Black Hawk helicopter from Rio Branco city at Acre state (AC) to Tarauacá city (AC), which are approximately 212 NM apart, there was a series of emergency lights related to failures in the aircraft's transmission and electrical systems going on (#1 GEN BRG, CHIP ACCESS MDL LH, CHIP INPUT MDL LH and CHIP MAIN MDL SUMP, in that order, with an interval of approximately 15 minutes between the first and last firing). In this situation, the aircraft was at a distance of about 90 NM from Tarauacá in a dense forest region, which does not allow the standard landing because the trees are approximately 50 meters high and there are no clear spaces. The only road in the area that connects the two cities were flooded and did not allow landing.

The helicopter had no satellite communication, and, in that position, the Very High Frequency (VHF) and High Frequency (HF) radios had no range to allow contact with other operators. For these reasons, the crew chose to continue flying to Tarauacá (AC), considering less risky the flight to the destination than landing in the forest.

Although there are procedures described for each of these emergencies listed above, there is no single procedure in case of occurrence of all these alarms together in the aircraft manuals.

1.2 H-60L Blackhawk helicopter presentation

The H-60L Blackhawk aircraft is a twin-engine helicopter whose maximum takeoff weight reaches 22,000 pounds and has a single main rotor configuration with a tail rotor structure.

Its T700-GE-701C engines work in parallel providing kinetic energy for both the main rotor and tail rotor. The main rotor and tail rotor are mechanically interconnected, with four blades constructed of titanium and fiberglass. The tail rotor has a lateral inclination to provide vertical support and the already traditional function of balancing the main rotor torque.

The main transmission is the structure responsible for transmitting the engines' kinetic energy to the main rotor and the tail rotor. The transmission is composed of several gear modules used to modify the direction from the turbine, which is parallel to the longitudinal aircraft axis, to the rotor blades' movement, which has its rotating axis perpendicular to the longitudinal plane. The gear modules also reduce the number of revolutions per minute and have an oil lubrication system. They also have an additional detection system of chips in the oil, which intends to identify a prematurely possible mechanical moving parts wear.

The importance of monitoring transmission conditions is emphasized, considering that there is no transmission system redundancy despite engine redundancy. In this way, a failure in the transmission system can be catastrophic for the helicopter's continued airworthiness.

1.3 Generator bearing fault caution light

The aircraft's AC electric power generator is directly coupled to the main transmission accessory box and is lubricated by helicopter main transmission oil. Inside the generator, a bearing is monitored using a sensor that detects unbalance and triggers the GEN BRG caution light on the caution and warning panel in case of parts loss.

There is no emergency action provided in the Checklist for the GEN BRG caution light, and the only activity that the crew must do is monitor the condition and limit the flight time for up to 10 hours after the respective light goes on, according to Figures 1 and 2.

2.58 AC POWER SUPPLY SYSTEM.

A primary ac power system delivers regulated three phase, 115/200 vac, 400 Hz. Each system contains a 30/45 kilovolt-ampere generator mounted on and driven by the transmission accessory gear box module, a current transformer, a generator control unit, and current limiter, all of which are interchangeable. System outputs are applied to the No. 1 and No. 2 ac primary buses. The **#1 GEN** or **#2 GEN** caution will appear whenever generator output is interrupted. The **AC ESS BUS OFF** caution appears when there is no power to the ac essential bus. Individual generator controls are provided on the upper console with marked positions of **TEST**, **OFF/RESET**, and **ON**. A generator main bearing caution system is installed on each main generator to activate the **#1 GEN BRG** or **#2 GEN BRG** caution to indicate a worn or failed bearing. The caution will appear until power is removed. The auxiliary bearing will allow 10 additional hours of operation after the caution appears. Therefore, it should not be a cause for mission abort. Power to operate the caution system is provided from the No. 1 and No. 2 dc primary buses through circuit breakers marked **NO. 1 GEN WARN** and **NO. 2 GEN WARN**, respectively.

Figure 1 and 2. Note on the H-60L generator bearing operation mode [1].

1.4 Transmission warning light emergencies procedures

Composed of gear that connects the generators and hydraulic pumps to the main transmission, the accessory modules (ACCESS MODULES) allow the operation of the components even in conditions of engine failure since the transmission is operating in its nominal rotation regime.

Composed of a conical gear, input modules connect the shaft of each engine with the main transmission module. The input modules promote the first reduction between the engine and the transmission, being identical and interchangeable.

The transmission oil lubrication system operates with two pumps in parallel, pressure regulators, by-pass valves, filters, radiators, and chip detectors in the accessory module (CHIP ACCESS MDL), in the input modules (CHIP INPUT MDL), and in the main transmission (CHIP MAIN MDL SUMP). Each module has a chip detector and, as metal parts immersed in the lubricating oil are captured, a MASTER WARNING general alarm light alerts the pilots as well as the specific emergency indication if there are chips in the right or left input modules in the right or left accessory module, or in the main transmission. The emergency actions provided in the Checklist for the emergency of chips in the input module are provided in Figure 3. For the accessory module or the main transmission is provided in Figure 4.

9.24.8 CHIP INPUT MDL LH or RH Caution Appears.

1. **ENG POWER CONT** lever (affected engine) - **IDLE**.
2. LAND AS SOON AS POSSIBLE.

Figure 3. Description of actions related to the chips in the input module emergency [2].

9.24.9 CHIP MAIN MDL SUMP, CHIP ACCESS MDL LH or RH, CHIP TAIL XMSN or CHIP INT XMSN/TAIL XMSN OIL TEMP or INT XMSN OIL TEMP Caution Appears.

LAND AS SOON AS POSSIBLE.

Figure 4. Description of actions related to the chips in the accessory module and the main transmission emergencies [2].

Item 9.24.8 defines the crew task to reduce the engine power on the input module side with input module chips indication, and as a subsequent action, the landing should be made as soon as possible. Item 9.24.9 defines that, in case of chips in the accessory module or the main transmission, the crew must proceed directly to the landing as soon as possible, without further action. The term LAND AS SOON AS POSSIBLE is described as an action to be taken without delay, where the primary concern is to ensure the safety of occupants, as described in the manufacturer's manual and illustrated in Figure 5:

> **9.3 DEFINITION OF EMERGENCY TERMS.**
>
> For the purpose of standardization, these definitions shall apply.
>
> a. The term LAND AS SOON AS POSSIBLE is defined as landing at the nearest suitable landing area (e.g., open field) without delay. (The primary consideration is to ensure the survival of occupants.)

Figure 5. Term LAND AS SOON AS POSSIBLE description [1].

2. Methodology

2.1 Cognitive Work Analysis

Stanton et al. [3] describe that Cognitive Work Analysis (CWA) corresponds to a structured tool specifically developed to analyze complex socio-technical systems. One of the main objectives is to model the system under investigation to identify improvements in processes and even standardize the tasks to be performed more effectively. Specifically, this work will be applied representations of Decision Ladder in the study of emergencies involving helicopters, as highlighted in Figure 6.

Thus, in general, the study developed in this article is based on the tools and methodologies introduced by Stanton [3]. In addition, the Decision Ladder, whose method will be used, is detailed next.

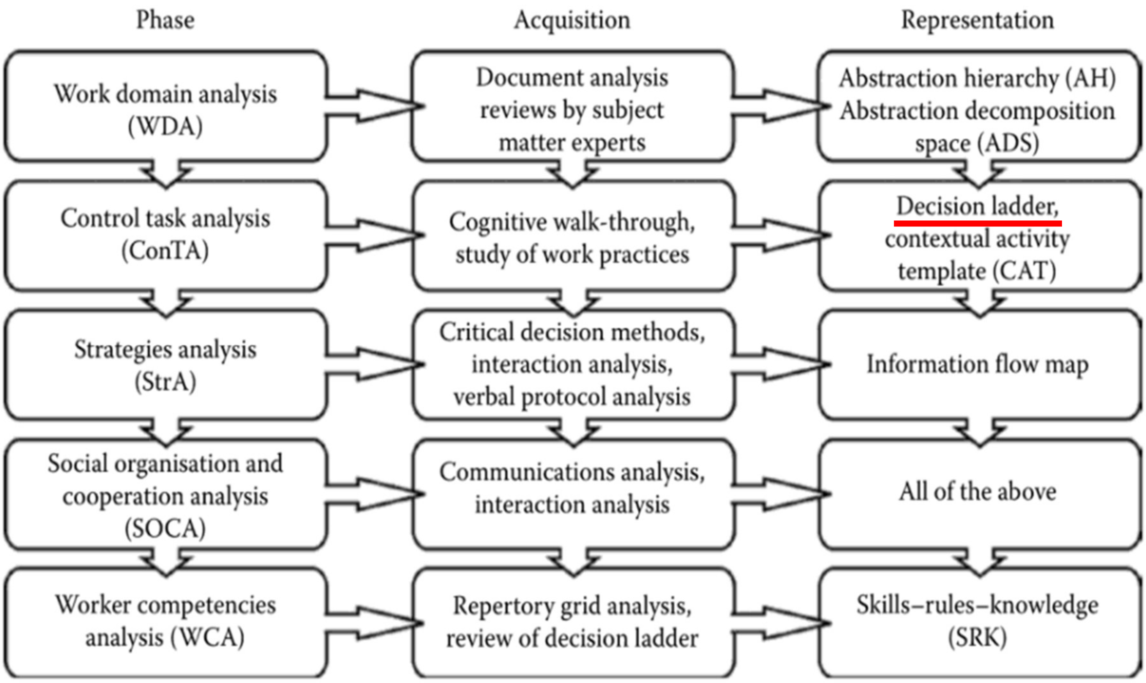

Figure 6. The CWA five phases [3].

2.2 . Decision Ladder

As indicated by Stanton et al. [3], the development of the decision ladder corresponds to a stage of ConTA (Control Task Analysis). It is also mentioned that Rasmussen's work [4] indicated that the different actions in a system could be described like the steps that a beginner would need to follow when performing a subtask. Following this approach, Stanton et al. [3] point out that rookies are expected to apply the decision ladder more linearly. At the same time, professionals who are more familiar with the operational context make shortcuts between the two parties. As stipulated by Stanton et al. [3], the basic representation of the decision ladder is indicated in Figure 7.

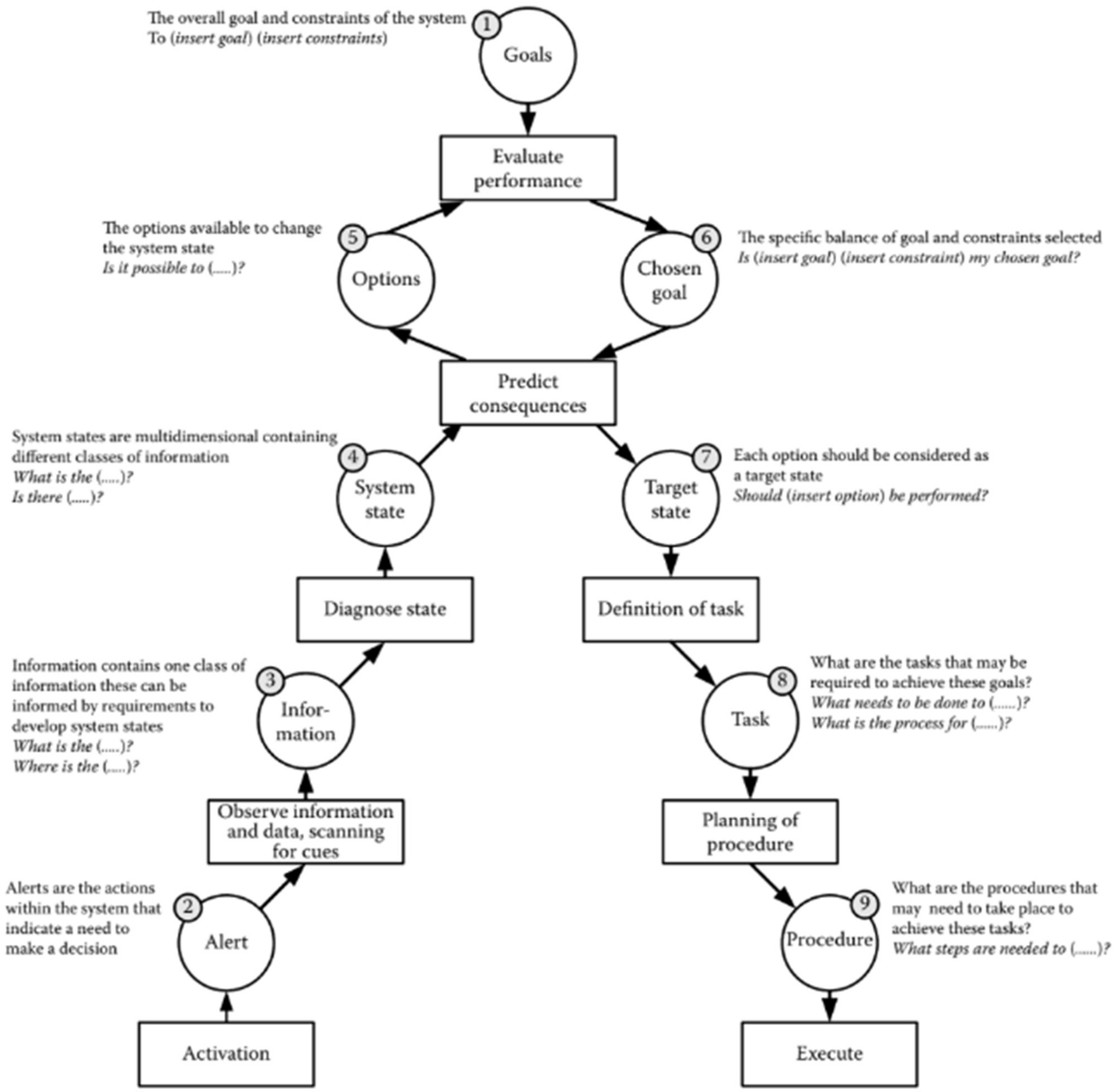

Figure 7. Basic decision ladder scheme [3]

The structure presented on the left represents the characterization of the system's current state; on the other hand, the one on the right highlights the planning and execution of tasks and procedures to achieve the intended target state. In the schematic representation of Figure 7, circles represent the system's state, while rectangles are the processing activity. Stanton et al. [3] point out that two types of shortcuts can be performed: "shunts" that link circles to squares and "leaps" that connect squares to squares. Figure 8 illustrates shortcuts in a hypothetical emergency in which there is oil leakage in an aircraft's engine. In this case, employing interviews with six pilots, the possibility of performing shortcuts in relation to SOPs (Standard Operation Procedures) was identified that could result in an early decision to shut off the engine.

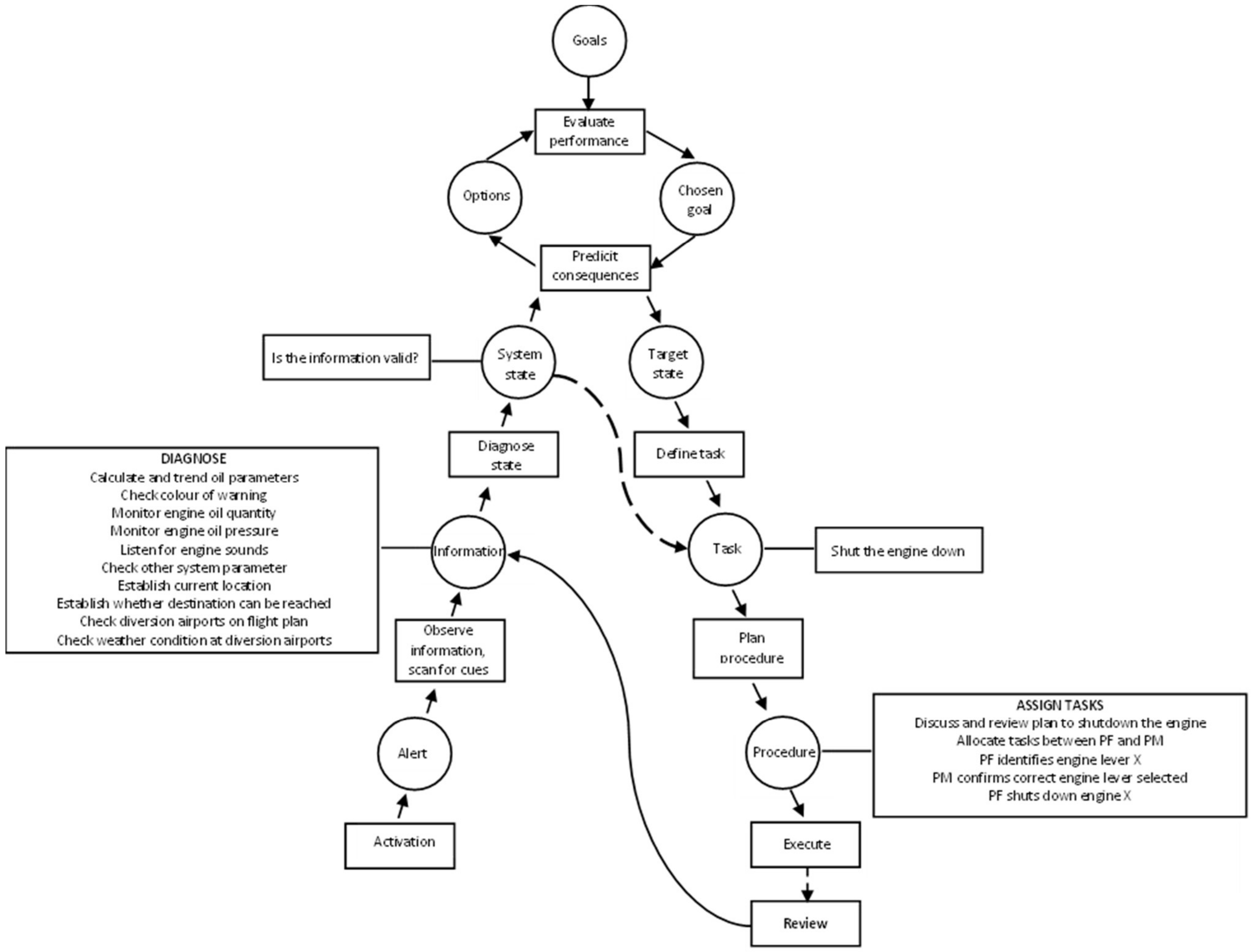

Figure 8. Shortcuts on the decision ladder for an emergency oil leak in an aircraft engine. Adapted from [5].

During the development of a decision ladder and the technical documentation and system design information under analysis, it is essential that experienced users participate. In the work developed by Asmayawati [6], the application of the decision ladder in emergencies related to the aircraft engine was studied. In the end, this modeling allowed to determine project design recommendations. As an example, as shown in Table 1, 7 pilots with different previous aircraft flying experiences and total flight hours were employed in this research. It is worth noting that all these pilots have experienced engine failure in their operational life.

This article will use two helicopters, experimental test pilots with flight experience and who have already experienced the emergency under analysis in a simulated environment and real flight.

As indicated in the work of Asmayawati [6], the necessary actions after a possible engine failure emergency were divided into three tasks: (WS1) Continue to fly the aircraft, (WS2) Perform the emergency actions, and (WS3) Modify the flight path. The description of each of these work situations is detailed in Table 2. Decision ladders were defined for each of these tasks, and the WS1 task is exemplified in Figure 9.

Participant number	Type rating	Engine on the aircraft currently flying	Approximate flight hours on current type (hours)	Past type rating	Approximate total fight (hours)	Rank	Length of service in current airline (years)	Age category (years)	Background	Operator (Airline)
A1	B787	RR Trent 1000	500	B737-300/400/500	5,000	Senior First Officer	3 - 5	31-40	Civil	A
A2	B777	RR Trent 800, GE 90	4,000	B757, B767	12,000	Senior First Officer	>10	41-50	Military	A
A3	A330, A340	RR Trent 700, RR Trent 500	10,000	A319, A320, A321	13,000	Senior First Officer	5 - 10	41-50	Military	B
A4	A320	IAE 2500	460	B737, B747-400	8,000	Captain	>10	31-40	Civil	A
A6	B777	RR Trent 800, GE 90	15,000	L1011, DC10	20,000	Captain	>10	51-60	Civil	A
A7	A330	GE CF6	2,800	A320, B737 EFIS, BAe 146	18,500	Captain	>10	41-50	Civil	C
A8	A330	GE CF6	3,000	A320, B737, BAe 146	17,000	Captain	>10	51-60	Civil	C

Table 1. History of pilots employed in the study regarding the application of the decision ladder for engine emergencies in aircraft. Adapted from [6].

Work Situation	Goal	Primary activities
WS1 – Flying the aircraft.	To ensure that the aircraft and its path are safe and under control following the event.	1.Regain and maintain control of the aircraft immediately following the PSM. 2.Confirm a non-normal situation that will need to be resolved. 3.Ensure safe flight path.
WS2 – Addressing the PSM	To identify the nature of the problem in order to select the appropriate checklist whilst maintaining sage flight.	1.Diagnose of PSM type and affected engine. 2.Select and confirm applicable checklist. 3.Apply checklist.
WS3 – Modifying flight plan.	To ensure a continued safe flight and landing at a suitable airport.	1.Review and assess aircraft and engine system capability. 2.Identify alternatives to flight plan. 3.Review revised flight plan. 4.Carry out and communicate revised flight plan. 5.Manage flight (and occupants).

Table 2. Shortcuts on the decision ladder for an aircraft engine oil leak emergency. Adapted from [5].

In aeronautical emergencies, other tools can be used to determine what decisions are required in the face of a specific scenario. For example, Rosa et al. [7] illustrate how simulation tools can be employed to compare decision criteria to success rates in an emergency.

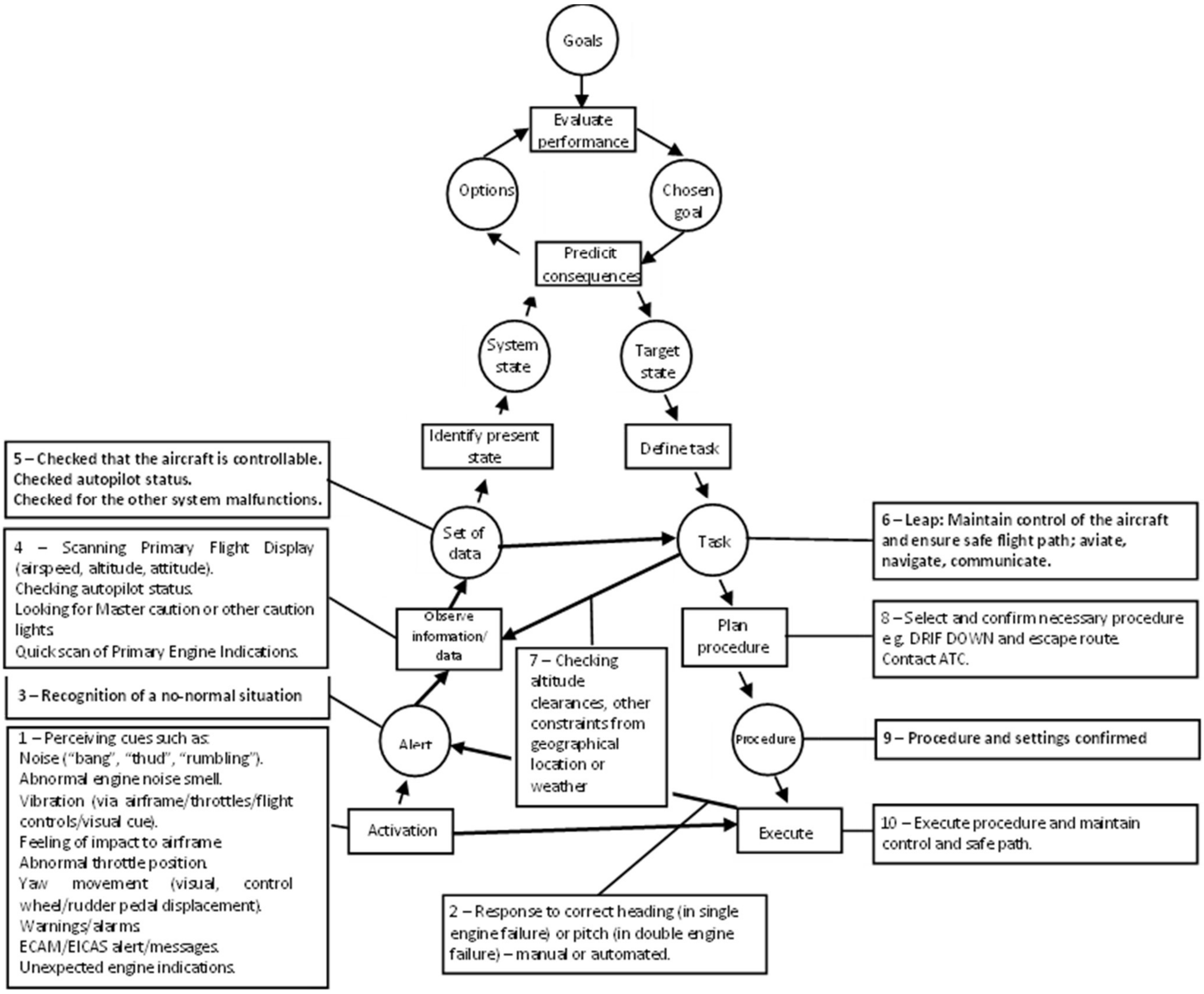

Figure 9 "Continue to fly the aircraft" task decision ladder and its respective shortcuts. Adapted from [6].

3. Discussion

The emergencies corresponding to the GEN BRG light and one of the CHIP ACCESS MDL LH /CHIP INPUT MDL LH /CHIP MAIN MDL SUMP lights were studied in different decision ladders, as illustrated in Figure 15. The results for the same flight conditions and operational scenarios were different due to the associated potential risk with each emergency: for the GEN BRG light, the decision output is to land as soon as practicable, and for the other lights, the output is to land as soon as possible.

Decision Ladder application analyzing a helicopter emergency

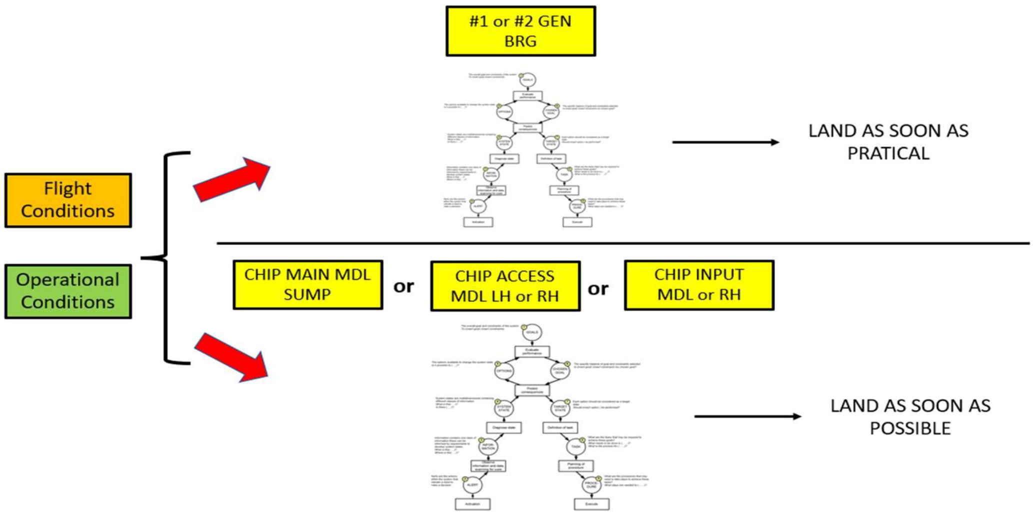

Figure 15. Schematic decision ladder for gen BRG light and one of the CHIP ACCESS MDL LH/CHIP INPUT MDL LH /CHIP MAIN MDL SUMP lights emergencies.

In the analysis after the hazardous situation, it was possible to observe that the loss of generator bearing parts produced chips that contaminated the main transmission oil. As the transmission has an unevenness where the input module is above the accessory box, which is higher than the main transmission sump, the CHIP lights have occurred due to the oil that flowed to the transmission's lower parts.

In this model, the possibility of a failure that would be common to the aircraft electrical system and the main transmission system was not considered. In addition, no different operational scenarios were evaluated since it was understood that there would be no interaction between these two systems.

For the crew, in addition to the advisory lights, the only knowledge that increased the situational awareness was the result of aircraft manual studies, which brought the concept that the same oil that lubricated the generator also lubricated the main transmission.

A complete evaluation of the scenario should be carried out to evaluate the best decision for the event. Using the order of Figure 10, it is possible to identify which steps were used within the decision ladder in the emergency procedure case study.

1. Goal: Operate the aircraft in such a way as to ensure the safest possible landing in an emergency aggravation. In this scenario, the mission would be degraded in favor of the crew's safety.

2. Alert: What additional clues would we have? What other alarms/indicators are direct or indirect could we have? Visual alarms #1 GEN BRG, CHIP INPUT MDL LH, CHIP ACCESS MDL LH, CHIP MAIN MDL SUMP lights up on the Caution/Warning panel.

3. Information: How to identify that there is an emergency? Other CHIP indications in the sequence? Change in aircraft vibration characteristics? Changes in the noise emitted by the transmission? #1 or #2 GEN light indicating generator failure? Oil leak from the outside of the aircraft? Changes in the required power of the aircraft (variation of TRQ with constant collective and/or constant speed)? Transmission oil temperature and/or pressure change? The smell of burning and/or the presence of smoke? Relevant maintenance information (e.g., recent maintenance action on the chip system)?

Previous history of enrollment failures, i.e., previous events that may be related (e.g., false alarms)? Abrupt yaw movements? Is there time to read the emergency checklist (this emergency item is memorized, but there is relevant information in the descriptive text of the emergency)? Is there other usable information in the flight manual? Is it possible to perform a landing as soon as possible (landing in these conditions will increase the consequences of an accident, for example, collision and breaking of the blades in the trees at the time of landing)? Will there be a rescue in the event of a landing as soon as possible? How long would a rescue take without the landing position being known?

4. System state: There was a generator loss (due to high temperatures and/or loss of transmission lubrication)? The severity of direct/indirect emergency evidence is progressing rapidly? There was confirmation of the information indicated in item 3 - Information?

5. Options: Is there time to perform a CRM with all crew members? Is there time to change the flight condition to a speed that requires less power? Is there time to reduce flight altitude? If the collective is reduced, the failure indications decrease in intensity? (E.g., the lower amplitude of torque oscillation, change in noise, and/or perceived vibration).

6. Chosen goal: The chosen goal was to "land as soon as possible" in the jungle? The objective chosen was to follow the parameters to try a landing in another location.

7. Target state: Is it possible to safely perform a "landing as soon as possible" in the jungle? Is it possible to track the parameters to try a landing at another location?

8. Task: Are all onboard properly tied up (preparing for an immediate landing)? Is the flight engineer is visual with the instrument panel to monitor flight parameters? Was CRM performed to measure the severity of the emergency? It has been confirmed what actions are needed for that type of emergency?

9. Procedure: Emergency procedure detailed in-flight manual TM 1-70-BrAF-10 depending on the characteristics of the emergency and judge the possibility of performing a landing as soon as practicable.

In the scenario in question, if the landing procedure were performed as soon as possible due to the transmission's chip light, the landing could have more severe consequences than those arising from the aircraft's failure, exposing the military on board to additional risks. The crew's judgment prevented a landing at an unprepared location in the Amazonian operational scenario, which could create catastrophic conditions needlessly.

Although this case study covers a wise crew decision, it was noticed that combined emergencies relating to the generator system and the main transmission lights are not provided in the flight manual. Therefore, it would be possible for another crew with a lower situational awareness to weigh less operational aspects and decide to land in the region with high trees.

The knowledge about the question indicated in item 3, "there is another usable information in the flight manual", made the difference in the experienced crew judgment. The crew had situational awareness enough to overcome the checklist procedure using the knowledge contained in the flight manual note combined with the information of oil commonality between the systems even when that is no description of this item in the emergency procedure itself.

At first, using the decision ladder methodology to classify the process, it is possible to realize that this decision was a shortcut from step 3 to step 9, which reinforces the theory because, with the information from the flight manual, the experienced crew was able to make decisions probably different from a less experienced one. This decision provided more time for the crew to review all the steps chosen to improve situational awareness and reformulate or validate the previous decision-making process.

Using the decision ladder methodology to look for any type of lapse in emergency procedures proved to be helpful. When there is no answer to one or more questions about the analyzed steps, there is a likely need to improve the task or the system. This methodology application in a post-event analysis proved to be useful because certification authorities, manufacturers, operators and flight safety agencies could use this process to identify critical steps that could be improved in design, technical publications or operational procedures.

Based on the steps used in the decision ladder analysis, it is suggested that the manufacturer and the aeronautical authorities evaluate the inclusion of a new emergency procedure that allows the helicopter crew to separate a probable risk situation (landing as soon as possible) from a lower gravity risk (landing as soon as practicable) improving the knowledge currently presented on the checklist to allow a less experienced crew follow in the same footsteps as an experienced crew.

Thus, in Figure 16, in a non-exhaustive way, it is suggested, in the case of simultaneous lights of GEN BRG, CHIP ACCESS MDL LH, CHIP INPUT MDL LH and/or CHIP MAIN MDL SUMP, and evaluation flowchart based on the available information. The purpose of this proposal is to allow the crew to have the possibility to decide on the need for immediate landing or not, according to item 3 of the decision ladder.

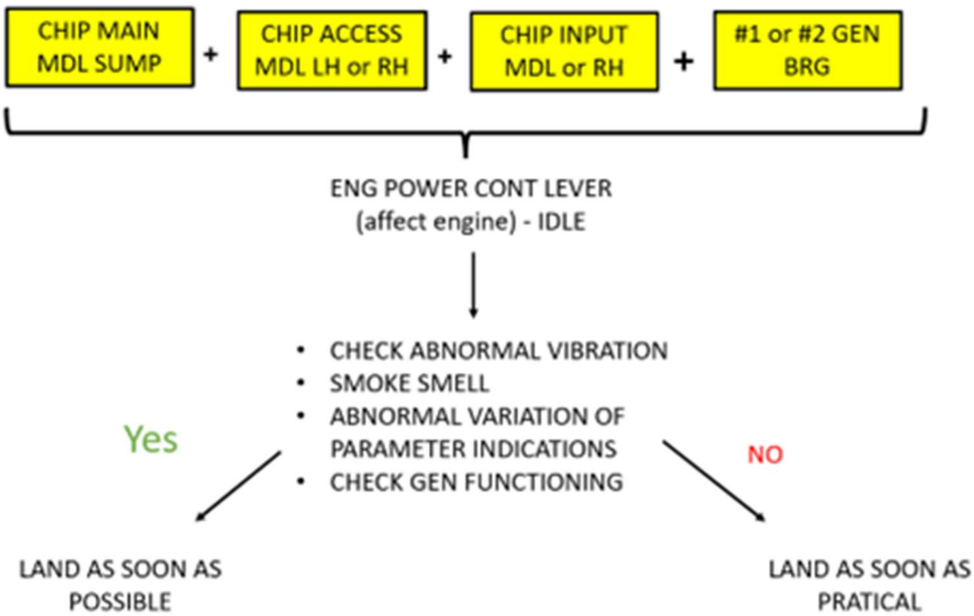

Figure 16. Emergency proposal to be evaluated for lights GEN BRG with CHIP ACCESS MDL LH, CHIP INPUT MDL LH and CHIP MAIN MDL SUMP.

4. Conclusion

The decision ladder used to evaluate an aeronautical emergency proved to be a robust and reliable methodology, and it is possible to consider aspects related to aircraft systems, operational and factors.

In the case study analyzed, it was possible to verify that the aircraft flight manual does not address the main transmission chips and generator system lights simultaneous occurrence, leaving to the operator the information evaluation from various sources for decision making. In order to prevent other crews from misinterpreting this type of occurrence, it was proposed to include a new emergency procedure based on the decision ladder analysis. It is worth mentioning that the practical application of this work's result depends on complementary evaluations at the certification level, for example.

In general, it was observed that the decision ladder used in a post-event analysis interpreting an aeronautical emergency could help identify relevant information and even improve existing procedures.

5. Copyright Statement

References

[1] Technical Manual – *TM_1-70-BrAF-10 Operator's Manual for Sikorsky S-70 Helicopter* – 1 November 2011.

[2] Technical Manual – *TM_1-70-BrAF-CL Operator's and Crewmember's Checklist* – 1 November 2011.

[3] Stanton, N.A., Salmon, P.M., Walker, G.H. and Jenkins, D.P. *Cognitive work analysis: applications, extensions and future directions*. CRC Press, Boco Raton, USA. 2017

[4] Rasmussen J., *The human data processor as a system component*: Bits and pieces of a model, Report No. RisØ-M-1722, Danish Atomic Commission, 1983

[5] Banks V. A., Plant K. L. e Stanton N. A., *Leaps and Shunts*: Designing pilot decision aids on the flight deck using Rasmussen's ladders, Contemporary Ergonomics and Human Factors CIEHF, 2020

[6] Asmayawati S. e Nixon J., *Modelling and supporting flight crew decision-making during aircraft engine malfunctions*: developing design recommendations from cognitive work analysis, Applied Ergonomics, Volume 82, Janeiro 2020

[7] Rosa E., Dahlstrom N., Knez I., Ljung R., Cameron M. e Willander J., *Dynamic decision-making of airline pilots in low-fidelity simulation*, Theoretical Issues in Ergonomics Science, Volume 22, 1a Edition, Pages. 83-102, 18 Maio 2020, https://www.tandfonline.com/doi/full/10.1080/1463922X.2020.1758830