Validating Assumptions About Pilot Recognition: A PCM-Based Approach for Aircraft Certification Safety Assessment Process

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Abstract

Recent notorious aircraft accident investigations have indicated the necessity of a deeper evaluation of the role of the pilot during failure conditions. One of the NTSB recommended actions for 737 MAX accidents explicitly requests the development of robust tools and methods to validate assumptions about pilot recognition of safety-significant failure conditions. The current guidance used by the industry for safety assessment (ARP 4761) presents the necessity of evaluation of crew workload and physiological effects but does not provide a structured methodology to evaluate pilots' interactions after failure conditions. This paper proposes to use the PCM structure to establish a framework for the evaluation of pilot recognition and response to failure conditions in the context of the Safety Assessment Process for aircraft development and certification.

Keywords: FHA, PCM, Safety assessment, Certification, Human Factors.

1. Introduction

The literature review established that the PCM is a suitable framework to model Aeronautical Critical Decision Making (ACDM) (ref. [[1]). The Perceptual Cycle Model presents a process-orientated approach to understand decision making by exploring the interaction between a person's cognitive schema, the actions they undertake and information available in the world.

Several articles use PCM as a tool for accident investigation (e.g., ref. [[3], ref [[8]), providing a framework to explore pilot's interactions with the aircraft and the relations of those interactions with the causes of the accidents. These studies resulted in insightful material for training improvements and better aircraft indications design.

The objective of this work is to demonstrate how Safety Assessment Process for development of new aircraft design can also benefit from the PCM structure for the evaluation of pilot recognition and response to failure conditions.

It is presented a framework to support the assessment of Failure conditions and some examples of applications of the method and the related discussions.

The investigations of the accidents Lion Air Boeing 737 Max 8, en-route Soekarno-Hatta (Indonesia) to Depati Amir (Indonesia), October 2018 and Ethiopian Airlines Boeing 737 Max 8, en-route Addis Ababa-Bole (Ethiopia) to Nairobi-Jomo Kenyatta (Kenya), March 2019 resulted in 189 and 157 fatalities, respectively, and total loss of the aircraft in both cases. The probable cause was the repetitive and uncommanded airplane-nose-down inputs from the MCAS.

The investigation found that this failure condition was predicted in the aircraft design, but it was not classified as critical due to the assumption of pilot recognition and immediate response to the failure, which were not the case in both accidents. One of the NTSB recommended actions for 737 MAX accidents requested the development of robust tools and methods to validate assumptions about pilot recognition of safety-significant failure conditions. (ref. [5])

Other accident investigations corroborate the necessity of better understanding the assumptions related to pilot recognition taken during failure conditions evaluations. Pitot failures of AF447 were also predicted during aircraft design but the actual occurrence of the failure completely surprised the pilots. The failure of the attempts to understand the situation and the de-structuring of crew cooperation fed on each other until the total loss of cognitive control of the situation. The underlying behavioral hypotheses in classifying the loss of airspeed information as "major" were not validated in the context of this accident. Confirmation of this classification thus supposes additional work on operational feedback that would enable improvements, where required, in crew training, the ergonomics of information supplied to them and the design of procedures (ref. [6]).

ARP 4761 provides guidelines for safety assessment activities for aircraft development and certification.
The evaluation of failure conditions follows Functional Hazard Assessment (FHA) process which is performed at the beginning of the development process, re-evaluated anytime significant changes are made to the aircraft, and used to establish the safety objectives for the functions to achieve a safe design. Failure conditions are analyzed for their effect on the aircraft, crew, and occupants to determine the associated severity classification (ref. [4]). The assumption related to the crew's ability to deal with the failure condition (recognition and associated procedures) defines some of its expected effects, being one of the most important assumptions to be evaluated during FHA.
The Failure conditions are classified according to their effects as presented Table 1:

Table 1 – Criteria for classification of failure conditions based on their effects for compliance with 25.1309(b) – Ref. [[7]

Effect on Airplane	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
Effect on Occupants excluding Flight Crew	Inconvenience	Physical discomfort	Physical distress, possibly including injuries	Serious or fatal injury to a small number of passengers or cabin crew	Multiple fatalities
Effect on Flight Crew	No effect on flight crew	Slight increase in workload	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatalities or incapacitation
Classification of Failure Conditions	No Safety Effect	<-----Minor------>	<-----Major------>	<--Hazardous--->	Catastrophic

In the documents mentioned above, there is no structured guidance for evaluation of effects on flight crew and the assumptions related to the pilot recognition as recommended by NTSB (ref. [5]).

2. Method

The PCM draws on Schema Theory to demonstrate how the environment and context surrounding the decision interact with the cognitive structures and actions of the decision maker (Ref. [1]).
Internally held mental templates (i.e., schema) help a person to understand situations and anticipate certain types of information; these schemas direct a person's behavior for seeking relevant information about 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. (ref. [9]).
The PCM has three key components "Schema," "Action," "World" which interact in a cyclic manner.

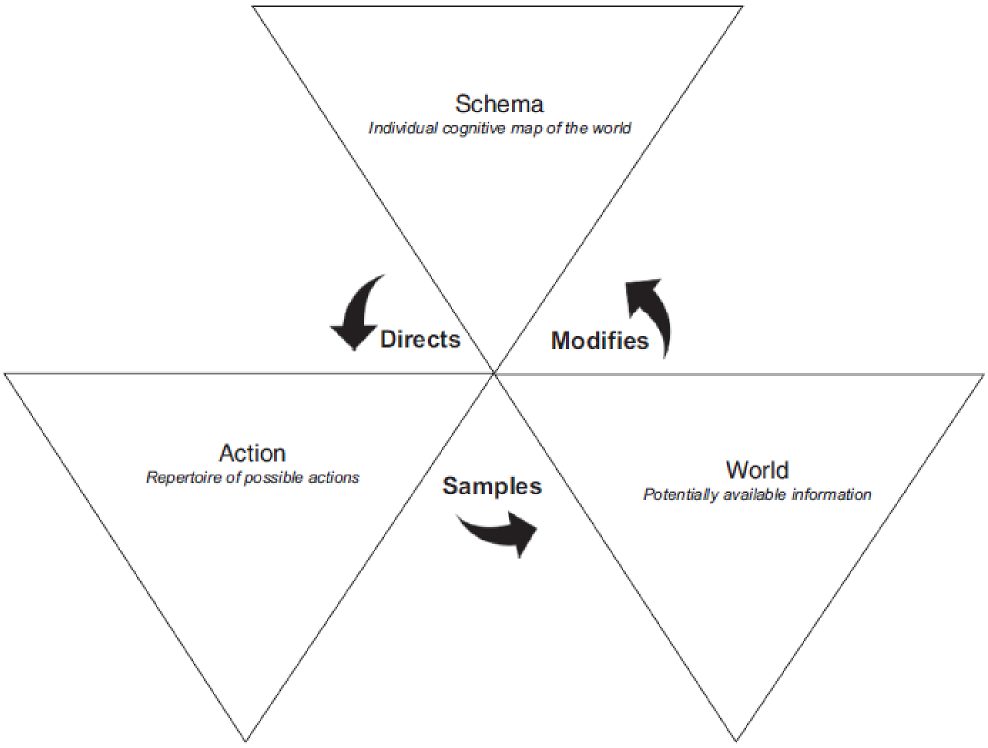

Figure 1 – Representation of PCM

PCM organizes the dynamics of the interaction between the human and the situation presented by separating the expected events (World), expectations and mental templates related to the noticed events (Schema), and the Actions in a cyclic manner. The failure conditions scenario dynamics can be structured in that same way to evaluate in more detail the pilot's ability to deal with a given failure condition:

- World: All noticeable behaviors (movement, sound, smell, smoke, sights etc.), messages, indications etc. expected during a given failure condition.
- Schema: Pilot's mental template for each set of aircraft behaviors presented to the pilot during a failure condition.
- Action: Procedures from basic airmanship or related to the messages / indications (QRH, AFM etc.).

In order to comprehend all the pilot's interactions during failure condition scenario, each of the processes in the PCM were coded to the different phases of the failure condition (ref. [[1]):

1. Onset of failure condition and associated immediate actions;
2. Results of primary actions, schema formulation and performance of procedures;
3. Schema Validation; and
4. Failure containment;

The first phase is related to the instinctive reactions following the failure condition, just a rudimentary schema is expected in this phase.
The second phase is associated with the formulation of a more elaborate schema that considers aircraft behaviors resulting from primary actions, failure messages and other indications. In this phase, pilots can execute procedures associated with the set of symptoms they are perceiving.
The third phase is the evaluation of the results of these procedures which will validate or not the schema elaborated in the second phase.
The last phase is related to the perception of the failure containment and remaining actions to assure the return of the aircraft to its normal state.
Figure 2, illustrates the PCM coded according to the different phases of the failure condition:

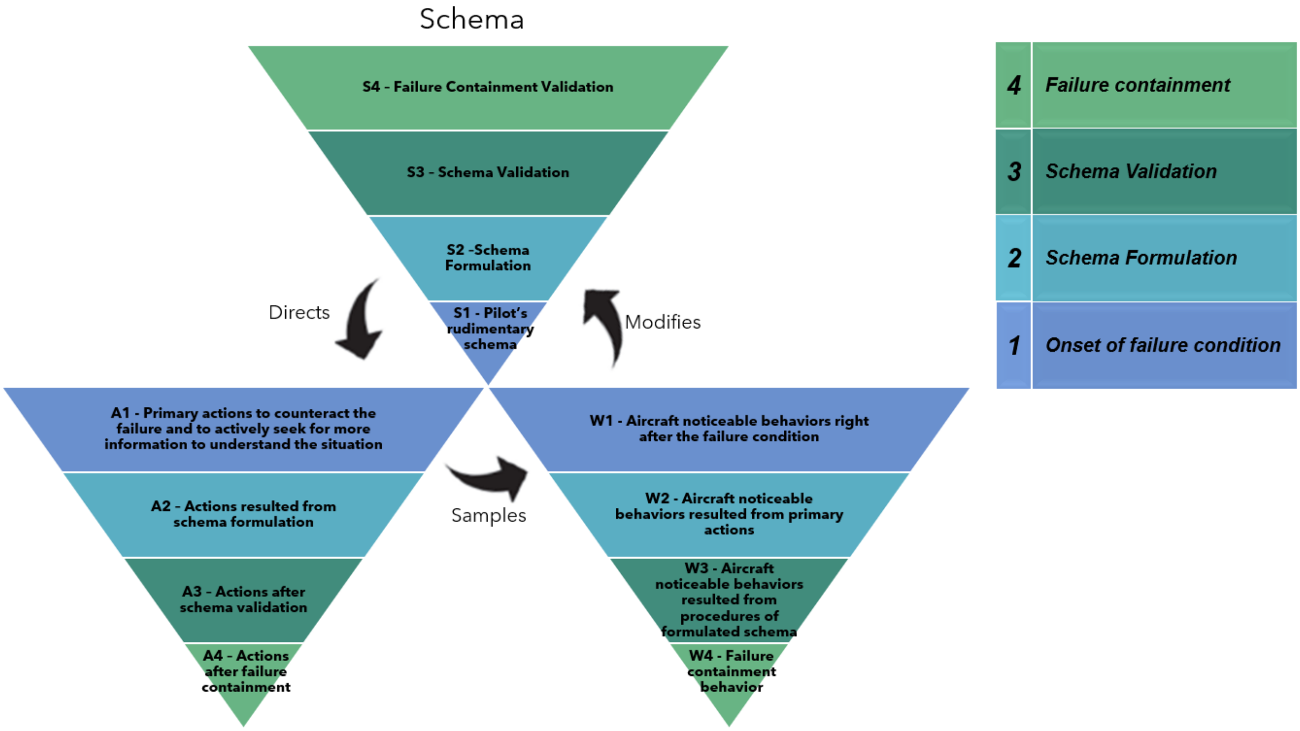

Figure 2 –PCM structure coded with different phases of the accident.

Pilot recognition and response of each relevant failure condition identified in the Safety Assessment Process can be evaluated using the PCM structure proposed in Figure 2. The list of information and questions raised during the PCM process establishes a framework that supports validating the assumptions of pilot's interactions during failure conditions.

Information required for failure conditions effects evaluation can be directly associated with information obtained using PCM. The component "world" of the PCM method represents the perception of the environment and can be associated with the aircraft failure effect evaluation of the FHA process. It comprises the sequence of events occurring during the failure condition, regarding aircraft behavior, messages, indications, etc. In the same way, the components "schema" and "actions" of the PCM method can be associated with the crew failure effects evaluation of the FHA process. It comprises assumptions related to pilot mental templates and the resulting actions following the noticeable aircraft behaviors, messages, and indications.

Table 2 provides a framework using the PCM structure (Figure 2) listing the information required and questions to be answered for validation of crew's ability to identify and respond to failure conditions.
It is recognized that not all the phases will be applicable for a given failure condition. Some failure conditions will not present any physical effect, others will not trigger any message or indication, some messages will not result in any procedure. The objective is to provide a framework that comprehends any kind of failure condition, and the applicable phases can be selected according to each failure condition characteristics.

Table 2 - Application of the method proposed listing all information required and questions to be answered for FHA validation.

CYCLE 1 - ONSET OF FAILURE CONDITION AND PRIMARY ACTIONS	
CODE	**INFO / QUESTIONS**
WORLD (W1)	**AIRCRAFT NOTICEABLE BEHAVIORS RIGHT AFTER THE FAILURE CONDITION.** **Questions:** **- Is there any aircraft behavior presented during the event? (e. g. movement, sound, smell, smoke, sights, messages)** **- Are there variabilities expected in the failure condition manifestation?**
SCHEMA (S1)	**PILOT'S RUDIMENTARY SCHEMA ASSOCIATED WITH THE NOTICEABLE BEHAVIOR OF THE AIRCRAFT.** **Questions:** **- Is it expected that the aircraft behaviors be associated with immediate actions from pilots? (basic airmanship)** **- Are these immediate actions effective in counteracting the failure?**
ACTION (A1)	**PRIMARY ACTIONS TO COUNTERACT THE FAILURE AND TO ACTIVELY SEEK FOR MORE INFORMATION TO UNDERSTAND THE SITUATION** **Questions:** **- What action is performed?** **- Is there any system that must be observed, checked or monitored to assist the expected actions?** **- Is there any other information available to contribute to the understanding of the situation?**
CYCLE 2 - RESULTS OF PRIMARY ACTIONS, SCHEMA FORMULATION AND EXECUTION OF PROCEDURES	
CODE	**INFO / QUESTIONS**
WORLD (W2)	**AIRCRAFT NOTICEABLE BEHAVIORS RESULTED FROM PRIMARY ACTIONS.** **Questions:** **- What is the aircraft's behavior after the primary actions?**
SCHEMA (S2)	**PILOT SCHEMA FORMULATION** **Questions:** **- Is there any procedure or training to react to the behaviors, messages and indications presented? If yes, what is it?** **- What are the predominant behaviors (the ones that call most attention from pilots)?** **- Is it possible to formulate a schema from the set of behaviors, messages and indications presented?** **- Is it possible to occur any misunderstanding between what is being perceived and what is actually happening?**
ACTION (A2)	**ACTIONS RESULTED FROM SCHEMA FORMULATION** **Questions:** **- What action must be taken from formulated schema?** **- Is there any system that must be observed, checked or monitored to assist these actions?** **- Is there any other information available to contribute to the understanding of the situation?**

CYCLE 3 – SCHEMA VALIDATION	
CODE	**INFO / QUESTIONS**
WORLD (W3)	**AIRCRAFT NOTICEABLE BEHAVIORS RESULTED FROM ACTIONS OF FORMULATED SCHEMA.** **Questions:** **- What is the aircraft's behavior after the actions?**
SCHEMA (S3)	**PILOT SCHEMA VALIDATION.** **Questions:** **- Are the primary actions sufficient to counteract the failure?** **- Is it possible to diagnose the failure? If yes, based on what information?** **- Is it possible to validate the primary schema?**
ACTION (A3)	**ACTIONS AFTER SCHEMA VALIDATION** **Questions:** **- Is there some system to be managed?** **- Is there some other procedure to be followed?** **- Is there any other information available to contribute to the understanding of the situation?** **If the schema is not properly validated ➔ Return to cycle 2**
CYCLE 4 – FAILURE CONTAINMENT	
CODE	**INFO / QUESTIONS**
WORLD (W4)	**AIRCRAFT BEHAVIORS AFTER THE FAILURE IS CONTAINED** **Questions:** **- What were the aircraft abnormal behaviors contained after the procedures?** **- Are there remaining aircraft's abnormal behaviors uncontained? If yes, is it critical?**
SCHEMA (S4)	**FAILURE CONTAINMENT VALIDATION** **Questions:** **- Is there sufficient information available to indicate the failure containment?** **- Is it possible that some hidden failure remained?**
ACTION (A4)	**ACTIONS AFTER FAILURE CONTAINMENT** **Questions:** **- What system must be monitored and managed to assure the failure containment?** **- What indications must be monitored?** **- What precautions must be taken after failure containment?**

3. Results

In the certification process of an aircraft, hundreds of systems failure conditions are expected to be assessed. For most of them, no big discussions about pilot recognition will be raised due to system simplicity or lack of integration/dependencies. The proposed technique shows its relevance in complex failure scenarios in which the systems integration plays a significant role in the cascading of events. Complex failure scenarios have the potential to occult its root cause leading the crew to waste precious time trying to understand the failure events and not to take the appropriate actions in a timely manner.
The case that demonstrated framework application were inspired on failure scenarios of accidents whose investigation provided vast information of the systems integration, failure effects and pilot interactions with the aircraft after failure conditions.

The section below is an application of the proposed framework to validate FHA assumptions related to pilot recognition and response to failure condition.

Failure condition: Erroneous AoA

- **Operational / Environmental Aspects**
  - Flight Phase: Climb
  - VFR
- **Assumptions to be validated from FHA:**
  - It is expected that the set of messages and aircraft behaviors provides sufficient information for the pilots to formulate the correct schema and perform the memory items and QRH procedures in a timely manner to counteract the failure condition.
  - The pilots must be able to fully contain the failure aspects that threaten the safety of flight and land safely in the nearest suitable airport.
  - The workload increase following the failure must be compatible to severity Major according to Table 1 (significant increase in crew workload).

Table 3 – Example of application of the method proposed for FHA validation.

CYCLE 1 - ONSET OF FAILURE CONDITION AND PRIMARY ACTIONS	
CODE	**INFO / QUESTIONS**

WORLD (W1)	**AIRCRAFT NOTICEABLE BEHAVIORS RIGHT AFTER THE FAILURE CONDITION.**
	
	<u>Questions:</u>
	- Is there any aircraft behavior presented during the event? (e. g. movement, sound, smell, smoke, sights, messages)
	- Uncommanded pitch movements.
	- Discrepancy in altitude and speed indications.
	- Failure messages:
	  - IAS Disagree
	  - ALT Disagree
	- Are there variabilities expected in the failure condition manifestation?
	- There are many ways in which the AoA indications might be erroneous:
	  o If the indication is too high, it will trigger automatic pitch compensations and stall protection devices (stall warning, shaker activation).
	  o If the erroneous indication is different between AoA sensors, it will trigger speed and altitude disagree messages.
	- Depending on the specifics of the failure condition some of the messages and warnings may be asynchronous, delayed, intermittent or not appear at all.
	- Uncommanded automatic pitch compensation may vary depending on flap position at the moment of failure.

<table>
<tr><th colspan="2">CYCLE 1 - ONSET OF FAILURE CONDITION AND PRIMARY ACTIONS</th></tr>
<tr><th>CODE</th><th>INFO / QUESTIONS</th></tr>
<tr><td>SCHEMA (S1)</td><td>PILOT RUDIMENTARY SCHEMA ASSOCIATED WITH THE NOTICEABLE BEHAVIOR OF THE AIRCRAFT.

<u>Questions:</u>
- Is it expected that the aircraft behaviors be associated with immediate actions from pilots? (basic airmanship)
Yes, Flight path changes result of uncommanded pitch movements lead to pitch command reactions from pilots to maintain flight level.
- Are these immediate actions effective in counteracting the failure?
Partially effective. Uncommanded pitch movements will remain.</td></tr>
<tr><td>ACTION (A1)</td><td>PRIMARY ACTIONS TO COUNTERACT THE FAILURE AND TO ACTIVELY SEEK FOR MORE INFORMATION TO UNDERSTAND THE SITUATION

<u>Questions:</u>
- What action is performed?
Counteract the failure with available elevator or stabilizer trim.
- Is there any system that must be observed, checked or monitored to assist the expected actions?
Monitoring aircraft primary flight information (attitude, altitude, and airspeed).
- Is there any other information available to contribute to the understanding of the situation?
Yes. Failure messages and aircraft indications.</td></tr>
<tr><td colspan="2">First Cycle - Comments
The variability of failure manifestations indicates the need to evaluate pilot responses in various scenarios to validate the proposed assumptions.</td></tr>
</table>

<table>
<tr><th colspan="2">CYCLE 2 - RESULTS OF PRIMARY ACTIONS, SCHEMA FORMULATION AND EXECUTION OF PROCEDURES</th></tr>
<tr><th>CODE</th><th>INFO / QUESTIONS</th></tr>
<tr><td>WORLD (W2)</td><td>AIRCRAFT NOTICEABLE BEHAVIORS RESULTED FROM PRIMARY ACTIONS.

<u>Questions:</u>
- What is the aircraft’s behavior after the primary actions?
- Uncommanded pitch movements.
- Discrepancy in altitude and speed indications.
- Failure messages:
  - IAS Disagree.
  - ALT Disagree.</td></tr>
<tr><td>SCHEMA (S2)</td><td>PILOT SCHEMA FORMULATION

<u>Questions:</u>
- Is there any procedure or training to react to the behaviors, messages and indications presented? If yes, what is it?
-Continuous nose down stabilizer trim inputs can be recognized as stabilizer runaway failure.
-Discrepancy in speed indications, IAS Disagree message and shaker activation can be recognized as an unreliable airspeed scenario.
-Discrepancy in altitude and ALT Disagree can be recognized as altitude disagree scenario.
- What are the predominant behaviors (the ones that call most attention from pilots)?
Continuous uncommanded pitch movements.
- Is it possible to formulate a schema from the set of behaviors, messages and indications presented?
Yes. At least three possible schemas can be formulated, but it is expected that stabilizer runaway scenario to be the prevalent schema associated with the behaviors perceived.
- Is it possible to occur any misunderstanding between what is being perceived and what is actually happening?
Yes. The failure scenario may indicate different causes.</td></tr>
</table>

<table>
<tr><th colspan="2">CYCLE 2 - RESULTS OF PRIMARY ACTIONS, SCHEMA FORMULATION AND EXECUTION OF PROCEDURES</th></tr>
<tr><th>CODE</th><th>INFO / QUESTIONS</th></tr>
<tr><td>ACTION (A2)</td><td>ACTIONS RESULTED FROM SCHEMA FORMULATION

<u>Questions:</u>
- What action must be taken from formulated schema?
Memory items for stabilizer runaway scenario.
- Maintain aircraft level through elevator and/or stabilizer trim.
- Disengage auto pilot and auto throttle.
- If the runaway continues ➔ Disengage stabilizer automatic trim.
- Is there any system that must be observed, checked or monitored to assist these actions?
Monitoring primary flight information.
- Is there any other information available to contribute to the understanding of the situation?
Failure messages and aircraft indications.</td></tr>
<tr><td colspan="2">Second Cycle - Comments
Three different schemas for the same set of aircraft behaviors indicate that following this failure condition pilot may not start the correct procedure to counteract the failure in a timely manner.
The choice of the predominant behaviors and associated schemas might be subjective considering the possible variability between actual failure manifestations and training scenario.
Additional differential indications are recommended to direct the pilot to the correct procedure.</td></tr>
</table>

<table>
<tr><th colspan="2">CYCLE 3 – SCHEMA VALIDATION</th></tr>
<tr><th>CODE</th><th>INFO / QUESTIONS</th></tr>
<tr><td>WORLD (W3)</td><td>AIRCRAFT NOTICEABLE BEHAVIORS RESULTED FROM ACTIONS OF FORMULATED SCHEMA.

<u>Questions:</u>
- What is the aircraft's behavior after the actions?
- Uncommanded pitch movements stopped.
- Discrepancy in altitude and speed indications.
- Failure messages:
  - IAS Disagree.
  - ALT Disagree.</td></tr>
<tr><td>SCHEMA (S3)</td><td>PILOT SCHEMA VALIDATION.

<u>Questions:</u>
- Are the primary actions sufficient to counteract the failure?
-Partially. The situation is under control, but the failure messages and disagree indications remain.
- Is it possible to diagnose the failure? If yes, based on what information?
-No, messages and indications remain.
- Is it possible to validate the primary schema?
-Partially. Actions resulting from this schema stabilized the situation, but some other symptoms are not quite understood.</td></tr>
<tr><td>ACTION (A3)</td><td>ACTIONS AFTER SCHEMA VALIDATION

<u>Questions:</u>
- Is there some system to be managed?
Yes, pitch trim system needs to be controlled manually.
- Is there some other procedure to be followed?
-Land at the nearest suitable airport.
-Procedures related to ALT Disagree and Unreliable airspeed might be followed.
- Is there any other information available to contribute to the understanding of the situation?
Failure messages and aircraft indications.
- If the schema is not properly validated ➔ Return to cycle 2
Not applicable</td></tr>
<tr><td colspan="2">Third Cycle - Comments
After the situation is under control some failure messages and disagreement indications remained which might confuse the pilots and lead them to follow unnecessary procedures.
The remaining messages, indications and abnormal behaviors after procedures completion must be advised in the manuals to provide clear indication that the correct procedures have been followed.</td></tr>
</table>

CYCLE 4 – FAILURE CONTAINMENT	
CODE	**INFO / QUESTIONS**
WORLD (W4)	**AIRCRAFT BEHAVIORS AFTER THE FAILURE IS CONTAINED** **Questions:** **- What were the aircraft abnormal behaviors contained after the procedures?** Uncommanded pitch movements. **- Are there remaining aircraft's abnormal behaviors uncontained? If yes, is it critical?** Failure messages and disagree indications remained. Those messages and indications are not critical.
SCHEMA (S4)	**FAILURE CONTAINMENT VALIDATION** **Questions:** **- Is there sufficient information available to indicate the failure containment?** Partially. The aircraft is controllable, but the failure messages and disagree indications remain. **- Is it possible that some hidden failure remained?** Yes. The root cause of some abnormal behaviors was not found.
ACTION (A4)	**ACTIONS AFTER FAILURE CONTAINMENT** **Questions:** **- What system must be monitored and managed to assure the failure containment?** Pitch trim system. **- What indications must be monitored?** Aircraft Attitude. **- What precautions must be taken after failure containment?** Aircraft must be controlled manually without Autopilot, Autothrottle and automatic pitch trim.
Fourth Cycle - Comments Conclusion of failure containment by the pilots might not be possible since some unexpected abnormal behaviors remained after procedures. The expected remaining abnormal behaviors must be advised in the manuals to provide a clear indication that the failure was contained after the procedures.	

Final Comments: The indications and procedures for the failure condition analyzed are not adequate to validate the assumptions of pilot's response to failure condition. The final aircraft's behavior remained abnormal and ambiguous, and failure indications remained being displayed. The results of applying the framework indicate the need for improvements in procedures and indications of failures, or ultimately, reclassification of the failure.

4. Conclusions

The proposed framework was applied in one fictitious case based on actual accident investigations.
It was demonstrated that the questions proposed were able to reveal problems in the assumptions related to pilot response to failures.
The first cycle questions were able to clarify some difficulties in the association between the actual aircraft behaviors after a failure condition and the training failure scenario due to the possible variability of failure manifestations and subjectivity in ranking the most important behaviors which the pilot will choose to counteract first.
In the second cycle the ability of the pilot to formulate a schema based on the failure messages, aircraft indications and physical behaviors was put in check. Several questions were raised about the assumption that following a complex failure pilot will perform a certain course of action. In the example, some doubts remained, and this assumption was not validated without additional design features and / or training.
The third and fourth cycle revealed that schema validation and failure containment identification were not ideal due to remaining failure messages which might confuse the pilots and lead them to not focus on the expected procedure to counteract the failure.
It was demonstrated that the compiled information and questions (Table 2) provide a robust framework to validate the assumptions about the pilot recognition of the failure conditions considering the dynamics of the failure, aircraft feedback, indications, pilot mental templates, pilot reactions and procedures.
A future work is recommended to revise the results with the support of a larger set of Pilots and HF Experts.

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