# Human Factors in the Pilot's Decision Making for Critical Scenarios

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## ABSTRACT

Brazilian Air Force (FAB) data from 2010 to 2019 revealed that 19.98% of accidents (first place on the list) and 13.86% (third place on the list) of incidents occurred during takeoff. In this critical phase of any flight, the pilot decides between rejecting or proceeding with takeoff after a critical failure. The cockpit of an airplane with two pilots and automation may be considered as a complex system, and human decision-making may be analyzed considering the degrees of freedom that each element has to generate alternatives and perform actions, mainly after failure events. The challenge is to identify, classify and mitigate hazards for better decision making. This article provides a structure to classify human errors related to the causes of an accident and to identify safety requirements. For this, the integration of two System Safety methods is used. First STPA is used to identify hazards and accidents, to develop a control structure, and to identify unsafe control actions and causal scenarios. Then, Rasmussen's SRK (Skill, Rule, and Knowledge) model is used to analyze the decision-making involved. This process is presented using the accident of the NOAR Flight 4896 as a case study. The result is a deeper understanding of the causes of the accident, which leads to better safety measures to prevent similar accidents.

## 1. INTRODUCTION

Complex problems are characterized by multiple actors, multiple perspectives, difficult to measure, and conflicting interests and key uncertainties [1]. In this scenario, the human is the element with the greatest variability in decision making, due to its degree of freedom to generate different alternatives and actions, and these without procedures can lead to error. The challenge is to identify, classify and mitigate hazards for better decision making.

As the technical aspects of aircraft flight were overcome, the role of people associated with the aircraft became more important. Initially, the pilots were supported with mechanisms to help stabilize the aircraft and, later, with automated systems to support the crew in tasks such as navigation and communication. With the introduction of highly complex systems, the interface between the pilot and the aircraft (displays) and the effects of one to another becomes very important. The study of the human/machine interface is called ergonomics and the application of this science is called Human Factors [2].

Today, the only phase of a commercial aircraft flight that does not have any automation is the take-off. The main reason for that is the level of complexity of the decision between rejecting or proceeding with the take-off after a critical failure. According to the FAA (Federal Aviation Administration), take-off accidents caused by improperly rejected take-off decisions and procedures (RTO) are significant contributors to commercial aviation statistics worldwide. The risks depend on the level of knowledge of the flight crew and the use of procedures. In the "low-speed regime" a takeoff must be rejected if there are: system failures, unusual noise or vibration, tire failure, abnormal acceleration, engine/fire failure, unsafe takeoff configuration, or a fire warning [2].

The European Aviation Safety Agency (EASA) presented statistics between 2009-2018 for airlines and for air taxi and cargo operations of Air Operator Certificate holders (EASA AOC), for airplanes with a maximum take-off mass

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greater than 5 700 kg. Their data revealed that accidents and serious incidents are frequent during take-off (21.5%), due to the critical nature of this phase of the flight [3].

According to Brazilian air force (FAB) data for airplanes, in Brazil, from 2010 to 2019, 19.98% of accidents (first place on the list) and 13.86% (third place on the list) of incidents occurred during takeoff. As for the most frequent contributing factors for accidents in this period, with 30.7% there is the judgment of piloting, application of commands, and managerial supervision [4].

Human factors covers a range of issues, including perceptual, physical, and mental resources. With interaction and effects on requirements and the work environment. Thus, there is the influence of system and equipment design on human performance, and organizational characteristics that influence behavior related to safety at work [5].

This article provides a framework for classifying human errors related to the causes of an air crash and identifying safety requirements. For this, the integration of two methods of Systems Safety is used. The first method is the STPA for the identification of hazards and accidents, the development of a control structure, the identification of unsafe actions and causal scenarios. Finally, Rasmussen's SRK (Skill, Rule, and Knowledge) model is used to classify the basis for decision-making. This methodology was applied to the case study of the pilot decision for flight NOAR 4896, based on the CENIPA accident report. The analysis explore the causes of the accident and reinforces the need for safety measures to prevent another accident for the same reason.

## 2. HISTORICAL EVOLUTION OF STUDIES IN THE SAFETY AREA

During the First World War (1914-1918), Operators' difficulties in using complex equipment have led to greater interest in the study of human limitations. In aviation, some concerns were the design of controls and displays, the effects of altitude, and environmental factors on the pilot. The war also revealed the need for aeromedical research and test and measurement methods. Thus, at the end of World War I, two major aeronautical laboratories were created, one at Brooks Air Force Base, Texas, and the other at Wright Field outside Dayton, Ohio [6].

During the Second World War (1939–1945), the difficulty of finding qualified labor for the new challenges was observed. So the aircraft project needed to undergo further studies in addition to meeting the military purpose, taking into account human limitations and capabilities. One example, carried out in 1947 by Fitts and Jones, studied the most effective configuration of control buttons for use on aircraft flight decks. This research served as a basis for other equipment in order to make the controls and displays easier to use for operators [6].

In 20 years after World War II, most research on human factors was carried out by Alphonse Chapanis, Paul Fitts, and Arnold Small. With the Cold War, the United States Department of Defense supported the expansion of research laboratories. Thus, most of the research after the war was sponsored by the military and much of the money was given to universities. The scope of the research has also been expanded from small equipment to workstations and entire systems [6].

In addition, the risk analysis area has also undergone an evolution over the years, as shown in figure 1. This was inspired by a slide by Erik Hollnagel presented at the 2012 Resilience Learning Lab in Vancouver, showing a timeline divided into four ages [7]. It reveals the post-war process, aligning human factors with the safety of operations. The first age was considering man as a tool, and the analysis of the hazards is based on what went wrong (Safety I). The second age reveals a greater study of human factors and the creation of a culture of safety in organizations. The third age was to consider how operations took place on a day-to-day basis, the work as done. The fourth age and the current focus on the adaptation of complex systems, as well as the variability of the elements.

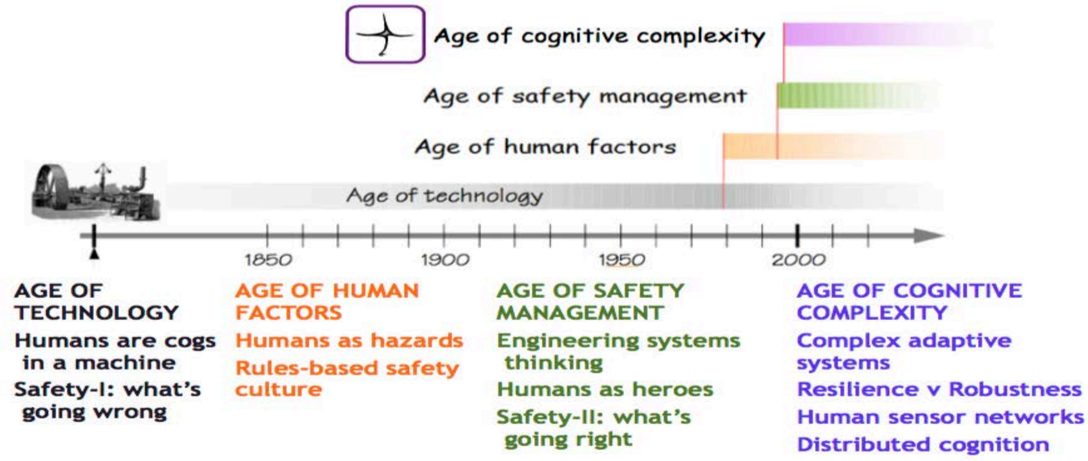


**Figure 1** – Evolution of safety studies [7].

In the cabin ergonomics, maintenance procedures, and air traffic workloads, all have the “human on the circuit” like a critical component that must be considered for optimal system performance, efficiency, and safety. With the advancement of science and technology over the years, the ability to measure, analyze and improve the human condition in aviation has also matured; related to pilots, maintenance technicians, controllers, or support professionals in this constantly evolving industry [8].

To finish this aviation safety research, in the last few decades, the Safety Management Systems (SMS) were conceived. The International Civil Aviation Organization (ICAO) developed standards for SMS practices for airlines around the world. Those standards are enforced by regulation of national aeronautical authorities.

### 2.1 *H*uman *F*actors

There is a tendency among human beings for complacency, with a belief that an accident will never happen to "me" or in "my company". It is not true that accidents happen only to irresponsible or "sloppy" people. Incidents and accidents show that mistakes can be made by experienced and respected individuals and can occur in organizations that were once considered "safe" [5].

In this field of research, the hazard is a potential source of harm; for example, a condition, object, or activity with the potential to cause injury to personnel, loss of materials, damage to equipment or structures [4]. An accident, on the other hand, leads to the worst scenarios or unwanted consequences. Accidents caused by human error, mechanical failure, or environmental problems can be avoided when "elementary events" are mitigated.  [9].

The human being is generally considered the most flexible element, but also the most critical in the system because people show considerable variations in performance and physiological limitations [8]. The term "human factors" is used in many different ways in the aviation industry and covers all aspects of human involvement in aviation, most people knew it in the context of aircraft cockpit design and Crew Resource Management (CRM) [5].

In summary, the field of Human Factors cover three areas of influence on people at work: The organization, The job, and Personal factors [5]. Figure 2 presents a list of some human factors for aviation in different areas of study.

**Performance and limitations**

- Vision; Hearing; Information Processing; Claustrophobia, Physical Acess and Fear of Heights.

**Social Psychology**

- Responsibility: Individual and group; motivation and demotivation; Peer pressure; culture issues; team working; management, supervision and leadership; maintenance resource management.

**Factors affecting performance**

- Fitness and Health; stress (domestic and work related); time pressure and deadlines; workload (overload and underload); sleep, fatigue and shift work; alcohol, medication and drug abuse.

**Physical Environment**

- Noise; fumes; illumination; climate and temperature; motion and vibration; confined spaces; working environment.

**Tasks**

- Physical work; repetitive tasks; visual inspection; complex systems.

**Communication**

- Within and between teams; work logging and recording; keeping up-to-date; dissemination of information.

**Figure 2** – Human Factors in aviation [5].

Therefore, we are in the Age of Cognitive Complexity, with the need to explore safety from a scientific perspective of non-linear complexity. Safety is not currently represented as a static product or service, but as an emerging property in a Complex Adaptive System (CAS) [7].

## 2.2 *S*TPA *M*ethod

Most accident prevention and investigation methods fall on the use of models considering a sequential and deterministic chain of events, in which the causality of the accident is described as a chain of failure and human error events that lead to the event with real loss. Among them: FMEA (Failure Mode and Effects Analysis, Failure Mode and Effects Analysis), FMECA (Failure Modality and Criticality Analysis, Failure Modes, Effects, and Criticality Analysis), FTA (Failure Analysis Tree, Fault tree analysis), ETA (Event Tree Analysis), HAZOP (Hazard and Operability Study, Hazard and operability study) and Cause - Consequence Analysis [10].

Such models are limited in their ability to deal with complex system accidents (resulting from interactions between components and not just individual failures), software-related accidents, high-complexity human decision-making, and adaptation or migration of the system hazards to an accident over time [11]. Within this concept, new methods have emerged that incorporate systemic thinking, the most cited being: Accimap, STPA, and FRAM [12].

In the study of risk analysis methods, it was found that since 1931, with the Domino Theory developed by Heinrich, researchers have approached that accidents occur from the interaction between system components, with visible or latent causes. Within this concept, new methods have emerged incorporating systemic thinking, with a qualitative analysis, that receive emphasis on Accimap by Jens Rasmussen (since 1997), Functional Resonance Analysis Method (FRAM) by Erik Hollnagel (since 2004), and Systems-Theoretic Accident Model and Processes (STAMP) by Nancy Leveson (since 2002) [10].

AcciMap is a technique developed by Rasmussen (1997) to generate proactive risk management strategies in complex socio-technical systems. It is represented as a cause and consequence flowchart, described at six levels: Government policy and budgeting; Regulatory bodies and associations; Local area government planning and budgeting/Company management; Technical and operational management; Physical processes and activities of an operator; Equipment and surroundings [13]–[15].

Hollnagel (2006) developed FRAM to investigate the conditions that can generate accidents between the stages of a process, through the mapping of their interdependencies. In this model, the risk analysis system considers the intraoperational functions (time, resources, and control) and the external functions (exit, entry, and precondition), generating a hexagonal structural function [12].

Among these three methods, this article will use the STPA considering its greater scope in the analysis of hazards and accidents. This has four steps: Define the purpose of the Analysis; Model the Control Structure; Identify Unsafe Control Actions (UCA); Identify loss scenarios [16].

The first step of STPA is to define the purpose of the analysis in four parts: 1- Identify losses; 2- Identify system-level hazards; 3- Identify system-level constraints; 4- Refine hazards (optional). The second step is to create a hierarchical control structure, which is a system model composed of feedback control loops. It seeks to develop an effective control structure that will impose restrictions on the system's behavior to mitigate hazards. The third step is to identify a UCA, which is a control action that, in an exact context and worst-case environment, will lead to a hazard. The fourth step is to identify the loss scenarios, which describes the causal factors that can lead to UCAs and hazards [16].

### 2.3 *M*odel *S*RK

A person's mental resources must be allocated to cover the demands of activity for that performance to be adequate (that is, with less chance of an accident occurring). However, humans have a limited mental capacity [16], and in daily life, the demands of the activity can exceed a person's limits. When this scenario occurs, the personal ability to process information, react to your surroundings, and make a decision is negatively affected, increasing the chance of accidents occurring [17].

Context is any information that can be used to characterize an entity's situation [18]. The entity is a person, place, or object seen as relevant to the interaction between a user and an application [17].

In this article, we will use the cognitive workload approach in the behavioral area, covered in the Rasmussen (1983) model known as Skill, Rule, and Knowledge (SRK). This model classifies human behavior at three levels:

(1) skill-based behavior (SBB) - occurs in a known context.

(2) rules-based behavior (RBB) - occurs in a family context, but with some differences.

(3) knowledge-based behavior (KBB) - occurs in unknown contexts [17], [19].

### 2.4 *C*ommercial *A*ircraft *T*akeoff *P*hases

According to CENIPA's data for airplanes, from 2010 to 2019 (Aeronautical Accidents Investigation and Prevention Center in Brazil), 19.98% of accidents (first place on the list) and 13.86% (third place on the list) of incidents occurred during takeoff. As for the most frequent contributing factors for accidents in this period, with 30.7% there is the judgment of piloting, application of commands, and managerial supervision [4].

First, some definitions are given about a regular commercial airplane takeoff.

It is customary for pilots to calculate takeoff speeds and therefore understand the operational importance of V1, VR, and V2. Takeoff speeds are a key safety element for takeoff and allow the pilot in command (PIC) to maintain a situational awareness to guide decisions in this very dynamic situation. In addition, the use of erroneous takeoff speeds can lead to tail strikes, high-speed takeoffs, or poorly performing initial climb [20].

In the take-off roll, it is extremely important to know the minimum speed at which the aircraft will remain directionally controllable in the event of an engine failure on the ground. In this situation, if the takeoff is continued, only the rudder will be able to neutralize the yaw moment generated by the asymmetric thrust of the engine (s) [20].

According to the regulations, the minimum speed at which an aircraft is defined as "controllable" (lateral excursion less than 30 feet, Figure 3) after an engine failure on the ground is referred to as $V_{MCG}$ (Velocity of Minimum Control on Ground). $V_{MCG}$ depends mainly on:

- Impulse of the engine (s)

- Pressure altitude [20].

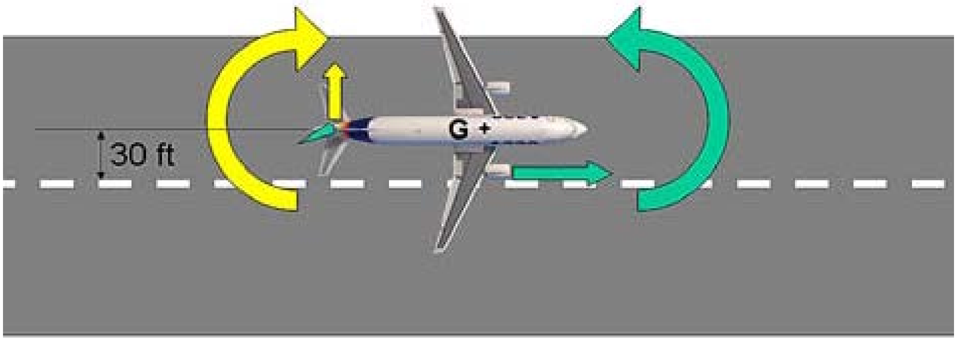


**Figure 3** – Human Factors [20].

If a failure occurs before reaching the $V_{MCG}$, takeoff must be stopped to maintain control of the aircraft [20].

$V_1$ is the maximum speed that still allows the rejection of the takeoff, in case of an emergency. This is a crucial decision exclusive to the pilot "Go / No-Go". V1 is also the minimum speed at which a pilot can continue to take off after an engine failure. If an engine failure is detected after V1, takeoff must be continued. Therefore, $V_1$ is always greater than $V_{MCG}$ [20].

$V_{MU}$ (Velocity of Minimum Unstick) is the minimum speed at witch the elevator can be used to its maximum up position without causing a tail strike during the takeoff [20].

$V_R$ (Rotation Speed) ensures that, in the event of an engine failure, takeoff is possible and $V_2$ is reached at a maximum of 35 feet [20].

$V_{MCA}$ (Velocity of Minimum Control in the Air) is the minimum speed at which the aircraft remains controllable with up to 5 degrees of bank angle, Figure 4. The rudder may used up to full deflection to compensate for the yaw moment caused by the asymmetric thrust [20].


**Figure 4** – VMCA [20].

$V_2$ (safe take-off speed) is the minimum speed that needs to be maintained up to the acceleration altitude, in the event of engine failure after $V_1$. The $V_2$ flight ensures that the required minimum climb gradient is achieved and that the aircraft is controllable. $V_2$ speed is always greater than $V_{MCA}$ and facilitates control of the aircraft in flight [20].

Besides, if an engine is lost before reaching $V_2$, the initial climb will be made in $V_2$. If the thrust is lost at a speed between $V_2$ and $V_2$ + 10, the current speed will be maintained, to ensure the most efficient ascent speed [20]. For visualization of the takeoff phases, see Figure 5.

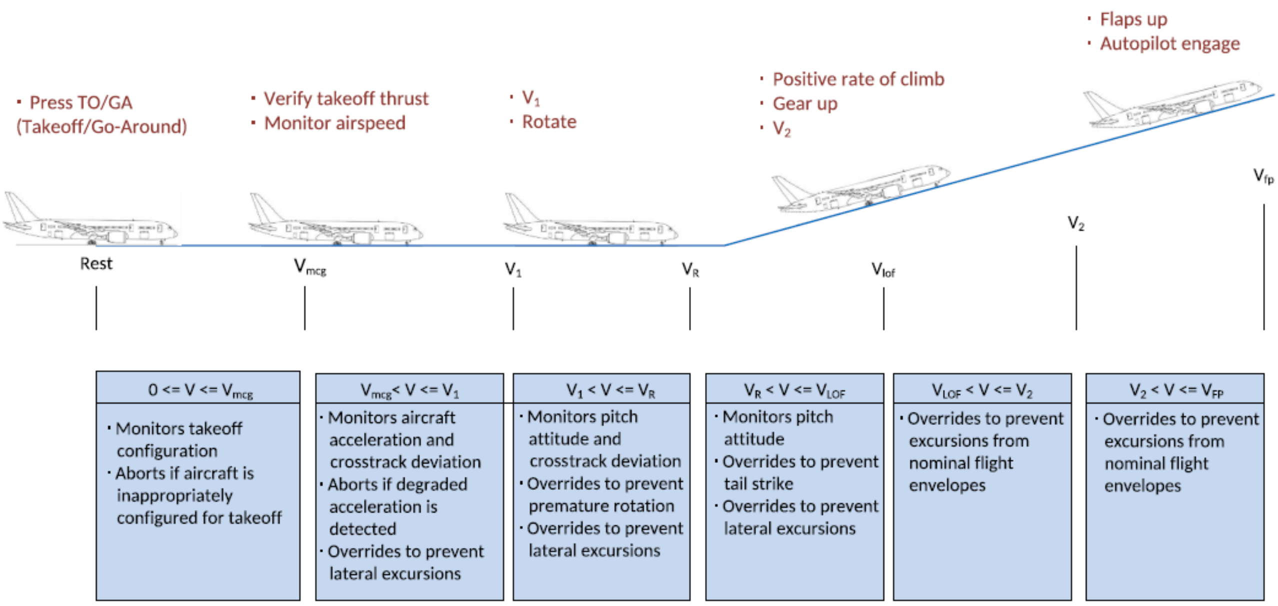


**Figure 5** – Flight crew and Flight Safety Assessment and Management (FSAM) functions during takeoff [21].

For more information on takeoff, visit the Pilot Guide to takeoff Safety [22].

## 3. CASE STUDY

This article will analyze the takeoff accident of Noar Linhas Aéreas Flight 4896 (July 13, 2011) and the pilot's decision to work around a hazardous situation. Figure 6 shows a Let L-410 Turbolet passenger aircraft in domestic service from Recife to Mossoró, Brazil [23].

**Figure 6** – Noar Flight 4896 [24].

According to a report by CENIPA, at 06h50 local time, the aircraft took off from runway 18 at Recife/Guararapes International Airport (SBRF), bound for Augusto Severo International Airport (SBNT) [25].

At takeoff, after the aircraft passed the runway's end, the copilot informed that he would return for landing, and requested landing on runway 36. The aircraft veered off to the left, out of the trajectory, passed the coastline, and subsequently, at an altitude of approximately 400 feet, started a right turn over the sea (Figure 7). After about 90º of the curve, the aircraft reversed the curve to the left, moving away from the coastline. Afterward, he made a turn of approximately 270º, leveled its wings, and headed to the airport area. Flying over the sea, the co-pilot informed that they would make an emergency landing on the beach [25].

Witnesses saw the aircraft crossing the shoreline and reported that the left propeller looked feathered and spinning freely. The aircraft collided with the ground in an area with no buildings, at 06h54 local time, between Avenida Boa Viagem and Avenida Visconde de Jequitinhonha, 1,740 meters from the runway 36 [25].

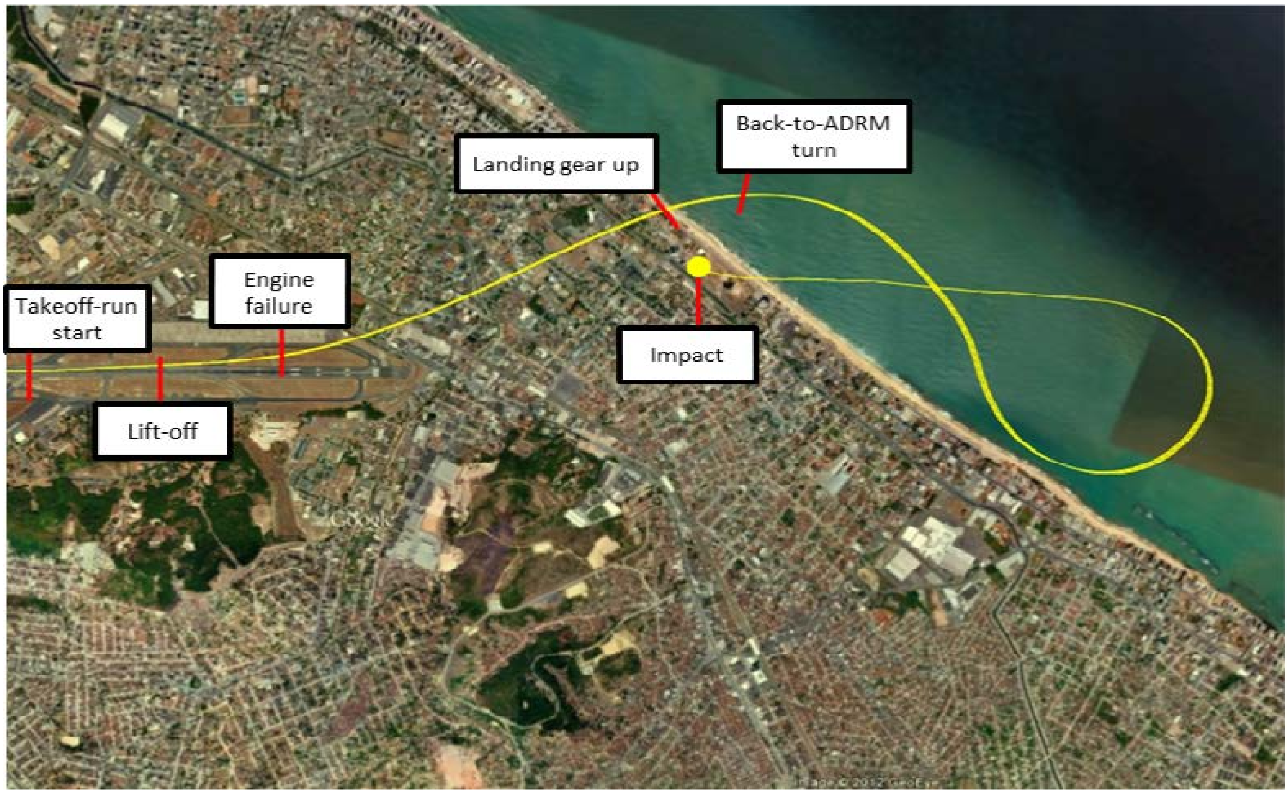


**Figure 7** – Flight trajectory according to the flight data recorder [25].

The engine failed shortly after the PIC requested the landing gear retraction, meaning the aircraft was above V1 and already flying. In other words, the procedure would really take off, considering the SOP (Standard Operating Procedures). However, it is possible that the co-pilot's attention was on the possibility of returning to the track. This would explain why the landing gear was not retracted right after the first request made by the PIC and the suggestion to "abort" the take-off upon learning of the engine failure (although the aircraft had already taken off), at that time the PIC replied that there was no enough space to stop [24].

Another crucial point found with the investigation is that the maximum takeoff weight provided by the software was 170Kg above the limit provided by the performance manuals issued by the manufacturer. In the case of flight 4986, there was an excess of 131 kg, which would imply a decrease of 39ft/min in the climb rate of 203ft/min, calculated for the single-engine condition [24].

In addition, in the manufacturer's checklist, the QRH (Quick Reference Handbook) item engine failure in flight was not found in the chapter on abnormal procedures, it was only present in the chapter referring to sections 3 and 3A of the AFM (Aircraft Flight Manual ) referring to an engine failure during takeoff. This research could hardly have been carried out in times of flight emergency [24].

The accident investigation highlighted deficiencies in Noar's training program for the L-410 aircraft concerning take-off engine failures, as well as discrepancies between the different versions of the aircraft checklists that were available to flight crews. CENIPA made several safety recommendations to Noar and Let on such issues, and to GE Aviation, owner of engine manufacturer Walter [23]. For more information about the accident, access the CENIPA report [24].

## 4. RESULTS

First, it was defined that the problem under study would be the study of alternatives to base the pilot's decision in a hazard scenario. This study seeks to assess a scenario similar to, but not specific to, the accident of flight Noar 4896, the expectation with the use of STPA is to provide a broad analysis for any type of aircraft and flight conditions.

In the first step of STPA, the following accidents were identified: A1-Loss of or damage to aircraft, A2-Loss of life or injury to people, A3-Environmental loss. The hazards considered were: H1-Aircraft with engine failure, H2- Aircraft tire burst, H3-Aircraft fire due to hi energy braking, H4-Aircraft with missing or inoperative equipment, H5-Collision with obstacles on the ground or in the air, H6- fail to reach the minimum climb rate, H7-Stalled aircraft, H8-Loss of situational awareness, H9- engine does not provide enough power.

In the case study, the result of the stall and explosion after the collision on the ground was mainly due to the failure of one aircraft engine, lack of communication between crew members to seek the best decision, and the lack of training for single engine controlled flight.

The second step of STPA was to build the control structure (Figure 8). In this case, only five elements will be considered. It is possible to observe who is the Controller (sends a control action) and who is the Controlled Process (receives the action for execution).

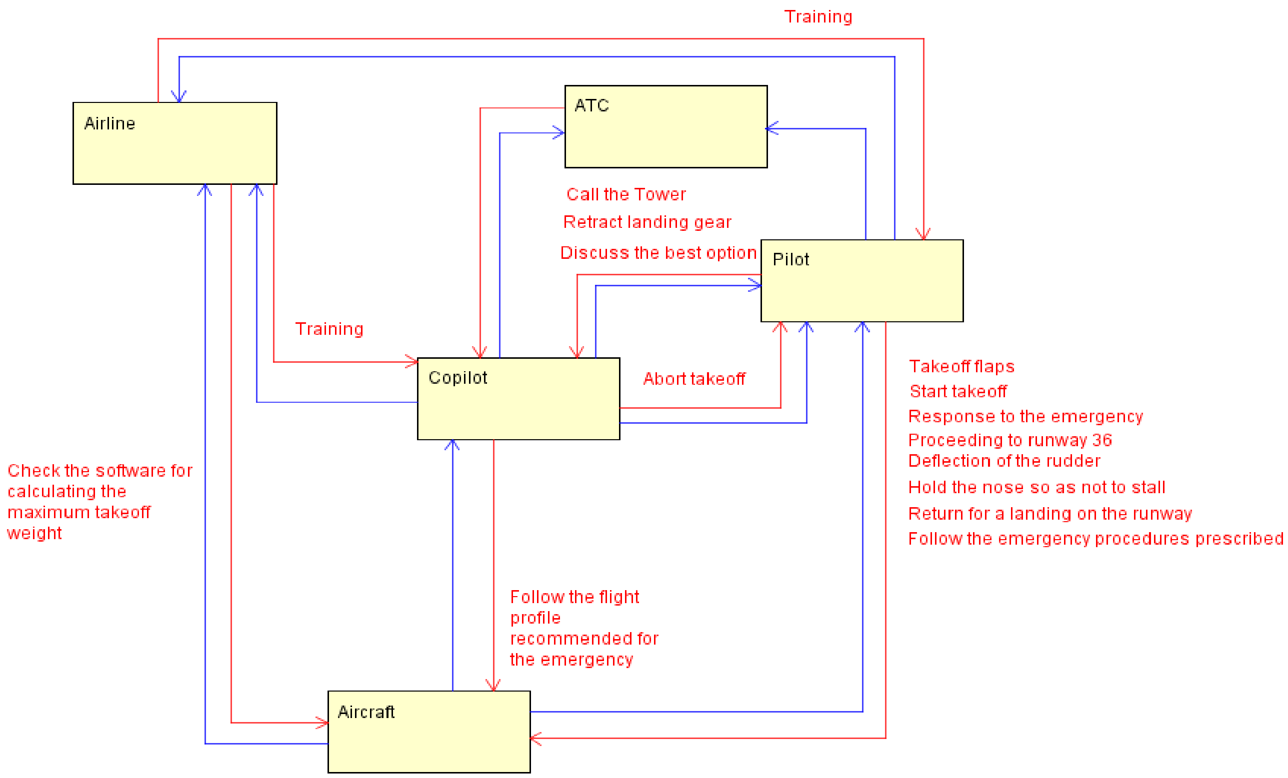


**Figure 8** – Flight crew and Flight Safety Assessment and Management (FSAM) functions during takeoff.

The third step of STPA is to identify the UCAs for each action in the Control Structure, that is, when the action became unsafe (time). These are shown in Figure 9.

| CA | From | To | CA Providing ... | Not Providing | Providing causes hazard | Too early / Too late | Stop too soon / Applying too long |
|---|---|---|---|---|---|---|---|
| Abort takeoff | Copilot | Pilot | | | | (UCA4-T-1) Co-pilot requests to abort the takeoff after v1 | |
| Training | Airline | Copilot | | | (UCA16-P-1) Ai rline provided in complete operat ional training pri or to flight opera tions. | | |

**Figure 9** – Flight crew and Flight Safety Assessment and Management (FSAM) functions during takeoff.

In the fourth stage of STPA, instead of identification, the scenarios will be classified together with the SRK model nomenclature, in order to explore how to simply classify the causes, type of decision base and mitigating action, Table 1.

**Table 1** – Classification of errors or failures related to each UCA [24].

| Action | Cause (Based on CENIPA report) | Skill-based behaviour | Rule-based behaviour | Knowledge-based behaviour | Violation | Actions of safety and security |
|---|---|---|---|---|---|---|
| Proceeding to runway 36 | Inappropriate judgment of the operational information presented | X | | X | | Study of Decision making process |
| Discuss the best option | Diverging ideas in cockpit revealed coordination problems that made it difficult to choose the best option for a safe landing | X | X | X | | Team dynamics Training |
| Training | The company's actions indicate informalities that impacted incomplete operational training and compromised safety. Airline provided incomplete operational training prior to flight operations. | X | X | X | | Organizational culture with safety priority |
| Deflection of the rudder | The pedal was not applied in a way that would allow a deflection of the rudder sufficient to maintain the coordination of the aircraft. Rendering it impossible to maintain a climb gradient or even a leveled flight. | X | | X | | Training for the application of flight controls |
| Hold the nose so as not to stall | Despite the stall alert and repeated requests by the copilot to not "hold the nose so as not to stall", the PIC continued acting in the pitch control until the aircraft reached a longitudinal attitude of 18º and stalled. | X | | X | | Training for the application of flight controls |
| Follow the flight profile recommended for the emergency | The lack of training of the takeoff engine failure above V1 emergency, in the exact way it is prescribed in the Training Program. The pilots did neither follow the flight profile recommended for the emergency, nor executed the checklist items prescribed after the 400ft. | X | X | X | X | Training |
| Return for a landing on the runway | The pilots judged that their priority would be to return for a landing on the runway, but in the opposite direction from the one they had used for taking off, with the turn starting at 400ft. Upon starting the turn, it would be necessary to find a new measure of pedal deflection compatible with the new condition of banking, and, at the same time, perform the checklist procedures. It is worth stressing that the operating engine had appropriate power for the maintenance of the flight. | X | X | X | X | Provide access to new studies for better pilot judgment |

The checklist format facilitates quick analysis, future statistical presentations, and clarity in the presentation of results.

## 5. DISCUSSION

This accident occurs after takeoff (above v1), with the engine failing right after the first PIC landing gear retraction request. This failure occurred because a gas generator turbine blade broke, just after the plane took off.

The results of the analysis show that the pilot and co-pilot had little time to decide in the face of a critical situation. It is also clear that some actions and communications between the crew were not aligned. There was also an informality in the training and commitment in the flight safety part by the airline, which hampered the pilot's lack of ability to keep the flight stable. It is noteworthy that there was mainly a lack of skill and rule/procedure for the actions taken during the specific emergency, which revealed and reinforces to this day the need for more training for the crew. As the engine failed shortly after takeoff, the pilot thought it would be possible to return to the runway and land. In "normal" conditions, it really would be possible, but the accident occurred due to the pilot's lack of skill and knowledge to deal with the critical scenario.

The SRK method reveals that lack of skill, knowledge and rule can lead to violation, and the STPA method reveals how the unsafe action scenario occurs and thus explores the details of the operation.

## 6. CONCLUSION

Although the study of human factors addresses different areas, in this article the study was in the analysis of the pilot's decision that, according to Rasmussen, is given based on the SRK model. The pilot's decision to return to the aerodrome (instead of other alternatives) was also explored, in the accident of flight NOAR 4896. It is important to note that the pilot only had about 4 minutes to decide, which reinforced the need for further studies to give the crew the skill, knowledge or rule (procedure) in adverse or hazardous scenarios.

The STPA method proved to be valid to reinforce the way to explore the decision and communication analysis between the aircraft crew. In this article, we intend to study how to analyze decisions in hazardous scenarios, and the methodology used allowed us to explore the identification of hazards and accidents to classify the reasoning that led to the decision, that is, what was missing for the correct decision.

This article also reveals that using the STPA method in conjunction with the SRK method is beneficial for identifying new safety requirements. For this test, an accident that has already occurred was taken as a basis, but it was possible to explore the details provided by CENIPA for a new application of methods. In addition, mistakes will always exist, the motivation to study the lessons learned is to avoid accidents with the same or similar mistakes.

## 7. ACKNOWLEDGMENT

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