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UNDERSTANDING PILOT DECISION-MAKING FAILURES IN ADVERSE WEATHER: AN HFACS AND BOWTIE DIAGRAM ANALYSIS OF HELICOPTER ACCIDENTS

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ABSTRACT

Aviation safety is maintained through rigorous adherence to established standards. However, certain pressure situations can compromise operational safety, making crews take unreasonable risk, like flying under adverse weather conditions. This paper aims to analyze helicopter accidents occurring in meteorological scenarios where flights should have been avoided, identifying patterns that influence pilots' misjudgment. This work uses two analytical frameworks: the Human Factors Analysis and Classification System (HFACS) and Bowtie diagrams, applied to four selected helicopter accident cases. The HFACS model systematically categorizes failures at four hierarchical levels (Organizational Influences, Unsafe Supervision, Preconditions for Unsafe Acts, and Unsafe Acts) whereas Bowtie diagrams visually map threats, preventive barriers, the critical top event, and mitigation barriers related to the accidents. The results consistently revealed organizational and self-imposed pressures influencing the decision-making of pilots to proceed under unsafe weather conditions, but these decisions were also shaped by additional factors, such as inadequate training, insufficient operational oversight, fatigue, poor risk perception, spatial disorientation, and misuse of onboard instruments, such as the meteorological radar. The Bowtie diagrams highlighted latent conditions, the inadequacy or absence of safety barriers, and the critical short timeframe available for mitigating actions once control was lost. The study concludes that enhancing organizational oversight, structured training, and proper understanding of avionic systems, particularly weather radar capabilities and limitations, are important to preventing similar accidents in the future.

Keywords: HFACS, Bowtie Diagram, Aeronautical Accidents, Flight Safety.

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GENERATIVE AI USAGE STATEMENT

The authors declare that the use of generative AI tools was restricted to technical support activities, without compromising the originality, analysis, and conclusions presented in the work. All information obtained through these resources was carefully evaluated and integrated into the study, ensuring methodological rigor and academic integrity. ChatGPT was used to review the text.

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1 INTRODUCTION

Aviation is internationally recognized as the safest transportation mode, an achievement that is far from incidental. Given the inherent risks of flight operations and the considerable stakes involved, demonstrated by the 118 million passengers transported in Brazil alone during 2024 (ANAC, 2025), this safety record stems from rigorous adherence to internationally established standards. Under the governance of the International Civil Aviation Organization (ICAO), global aviation safety is maintained through programs like the Universal Safety Oversight Audit Programme (USOAP), designed to assess and reinforce the safety oversight capabilities of member states (International Civil Aviation Organization, 2025). These regulatory frameworks cultivate a proactive approach focused on continuously learning from past incidents to prevent future occurrences.

In Brazil, aviation is a shared responsibility between the National Civil Aviation Agency (ANAC) and the Brazilian Air Force (FAB), specifically through its Aeronautical Accident Investigation and Prevention Center (CENIPA) and Regional Services (SERIPA), components of the Aeronautical Accident Prevention System (SIPAER) (Brasil, 2018). The central philosophy of this system emphasizes learning and preventive action rather than punitive measures, ensuring that each incident contributes meaningfully to ongoing safety improvements. This feature ensures that each adverse event contributes to reducing the likelihood of future accidents, thereby incrementally increasing system safety over time.

This structured, learning-oriented safety culture is notably absent in other Brazilian transport sectors. For instance, road transport consistently causes approximately 33,000 deaths annually (Associação Nacional de Medicina do Trabalho, 2024) (a statistic that only accounts for fatalities at the scene). The disparity underscores ICAO's effectiveness, as a global governing body, in ensuring that even countries with high accident rates in other transport domains comply with aviation safety regulations making them achieve globally recognized standards of excellence.

However, aviation comprises multiple branches such as executive, commercial, agricultural, and military aviation (the latter increasingly employing Unmanned Aircrafts (Casale *et al*., 2024)). There is a notable lack of uniformity in safety standards among these segments. Commercial aviation, for instance, exhibits the lowest accident rates, whereas agricultural aviation registers a higher frequency of undesirable occurrences (Maliszewski, 2021). In executive aviation, unique pressures can compromise operational safety. Hierarchical dynamics, such as when a client is also the aircraft owner and the pilot's employer, may compel pilots to fly in unsafe conditions to protect their employment. Similarly, the desire to retain high-value clients can pressure aviation companies and their crews to approve flights under elevated risk, such as in adverse weather conditions, to avoid potential financial repercussions.

This underscores that aviation safety is influenced not only by human and technical factors but also by organizational ones. In this context, the Human Factors Analysis and Classification System (HFACS) offers a valuable framework for understanding the different layers of contributing factors in aviation accidents.

Based on James Reason's Swiss Cheese Model (Reason, 1990), HFACS was developed by Scott Shappell and Doug Wiegmann for the U.S. Navy. The model emerged as the focus of accident analysis shifted from technical failures to human and organizational factors. HFACS categorizes contributing factors into four hierarchical levels: Organizational Influences, Unsafe Supervision, Preconditions for Unsafe Acts, and Unsafe Acts (Wiegmann & Shappell, 2003). Its purpose is to systematically identify human factor failures to guide preventive measures and corrective training programs (Small, 2020). Effective application requires distinguishing between prescribed procedures and actual performance to properly identify contributing factors at all organizational levels (Correa & Cardoso Junior, 2007).

Another framework adopted across various high-risk sectors, including aviation, oil and gas, nuclear power, and healthcare, is the Bowtie diagram, a graphical method for representing and analyzing risk scenarios, structured to illustrate the causal pathways that link threats to potential adverse consequences. The first Bowtie diagrams reportedly appeared at The University of Queensland, Australia, in 1979, though the method's exact origin remains unclear (Wolters Kluwer, 2025). This visualization tool demonstrates how a particular hazard can materialize through distinct threat mechanisms, depicted on the left-hand side of the diagram, and subsequently progress to diverse negative outcomes or consequences, shown on the right-hand side. Central to this representation is the concept of the "top event," positioned at the midpoint of the diagram, serving as the pivotal moment at which the scenario transitions from a controlled to an uncontrolled state, thereby initiating a cascade of events toward undesirable consequences (Center for Chemical Process Safety, 2018).

The utility of the Bowtie diagram emerges from its structured depiction of risk management barriers. Preventive barriers, represented between threats and the top event, aim to reduce the likelihood of a hazard materializing. Conversely, mitigative barriers, positioned between the top event and the potential consequences, focus on limiting the severity or impact of outcomes once control is compromised (Voicu *et al.*, 2018). It is noteworthy that the threats depicted on the left side of the bowtie diagram are typically latent, evolving gradually within the scenario and often remaining active for extended periods before culminating in a top event. As a result, preventive barriers designed to counteract these threats generally do not require rapid reaction capabilities. In contrast, the consequences on the diagram's right side tend to manifest swiftly, leading rapidly to undesirable outcomes. Consequently, the recovery (mitigative) barriers positioned to the right of the top event must function with immediate effectiveness to prevent or mitigate adverse impacts. This twofold approach allows identifying vulnerabilities, evaluate the effectiveness of existing control measures, and systematically implement additional safeguards to enhance resilience.

Several factors are associated with the occurrence of undesired events in aerospace activities and may justify the postponement or cancellation of missions, such as environmental and atmospheric conditions (Caruzzo *et al.*, 2021). However, organizational factors can influence decisions to initiate or continue missions even under unfavorable weather conditions, thereby assuming elevated risks.

The application of both HFACS and Bowtie is well-established in aeronautical safety literature (Bills *et al.*, 2023). Numerous studies have applied HFACS to investigate accidents in aviation, and new approaches have evolved proposing integrating Artificial Intelligence into HFACS analysis to improve aviation safety (Liu *et al.*, 2025). Similarly, the Bowtie method has been widely used for proactive risk management in areas such as runway safety, maintenance procedures, air traffic control, and flight training (Leitão *et al.*, 2022), effectively visualizing how safety barriers can prevent or mitigate undesirable events.

Prior research has indicated that pressure to fly (institutional or self-imposed) can make pilots prone to keep flying in adverse climate conditions, but this factor isolated can't explain their decision to resume the flights. If they decided to continue flying, it is because they assessed that it was safe enough. In other words, for some reason, they did not identify the real hazards present in the situation, and somehow judged that they would succeed in managing the bad weather conditions and finishing their missions.

In this context, aiming to identify potential patterns associated with accidents involving rotary-wing aircraft that occurred under weather conditions in which flight should have been avoided, this study seeks to apply the HFACS (Human Factors Analysis and Classification System) and Bowtie methods to analyze helicopter accidents under adverse meteorological conditions and to examine, besides the pressure to fly, which factors contribute to the misjudgment of the pilots to believe that they could continue flying under such bad conditions.

2 METHOD

This study employs a qualitative approach, and the accidents were selected based on the following criteria: (1) they involved helicopter operations; (2) adverse meteorological conditions were present; and (3) official investigation reports were available. The HFACS coding process was conducted by mapping the contributing factors identified in the reports onto the corresponding categories within the four levels of the framework. As the number of cases studied is small, the findings are not intended to be statistically generalizable, but to illustrate recurring patterns and systemic vulnerabilities that warrant further attention, offering deep insights into the dynamics of the selected events.

3 ACCIDENT ANALYSIS

In this study, three accidents were selected for analysis using the HFACS (Human Factors Analysis and Classification System) framework and Bowtie methods, which will be presented below.

3.1. Final Report A-157/CENIPA/2016

On December 4, 2016, at approximately at approximately 3:00 p.m. local time, the aircraft PR-TUN, model R44 II, departed from the Osasco Heliport in route to an event venue in the municipality of São Lourenço da Serra, carrying one pilot and three passengers.

The aircraft was in airworthy condition, with valid licenses, documentation, and maintenance records up to date. The pilot held a valid license, had experience with the aircraft model, and possessed an up-to-date medical certificate. However, the accident report identified shortcomings in the documentation of his training and noted deficiencies in the pilot's performance during emergency procedures training. Although formally employed, the pilot did not have a regular flight schedule and was often called upon with little notice, which may have contributed to an environment of operational instability and urgency.

The flight in question was intended to transport a bride and two companions to the location of her wedding ceremony. Given the special nature of the occasion, several moments of the flight were recorded by the passengers, and these recordings, including key video frames, were used in the investigation and presented in the final report.

During the flight, weather conditions progressively deteriorated until the aircraft encountered Instrument Meteorological Conditions (IMC). This type of operation is prohibited for the R44 II model, which is not certified for instrument flight, and the pilot was not qualified for such operations. Nevertheless, the pilot chose to continue the flight in an attempt to reach the destination, but ultimately lost control and crashed almost vertically. The aircraft was destroyed, and all occupants sustained fatal injuries.

Table 1 presents the HFACS analysis of the accident, highlighting the contributing factors identified in the official report. It can be noticed that pressure to complete the flight may have influenced the pilot's decision to continue under adverse meteorological conditions, the report indicates that the pilot was frequently summoned on short notice, which may have created a sense of urgency to fulfill flight tasks. Given the emotional significance of the event for the bride, the passengers' expectations to arrive at the ceremony, and the aircraft's proximity to its destination, these elements may have influenced the pilot's decision to proceed. It is also noteworthy that, at the time of the accident, the pilot had been formally employed by the operating company for only about two months, and this was his first formal aviation job with a fixed salary. This may have contributed to a perceived need to satisfy employer or passenger expectations, so as not to jeopardize his employment.

Nevertheless, this factor alone does not fully explain the decision to continue the flight. The pilot appeared confident that reaching the destination was feasible; otherwise, he likely would have aborted the mission. So, omissions in his training records and his limited experience contributed to a lack of risk perception regarding the flight conditions he encountered. Moreover, he was unprepared to manage the emergency situation and relied solely on GPS indications, disregarding the aircraft's original instruments, which were providing conflicting information in relation to GPS. This reliance led to spatial disorientation, compromised the helicopter's stability, and ultimately resulted in the crash. Therefore, the pilot's lack of experience, inadequate training, and insufficient knowledge of adverse weather flight conditions fostered an overconfidence that led him to underestimate the risks and believe he could complete the mission.

Table 1: HFACS analysis for Final Report A-157/CENIPA/2016.

HFACS Level	Category	Classification Based on the Report
Level 1 Unsafe Acts	*Violations*	**Applicable**. Decision to continue the flight in IMC conditions despite the aircraft and pilot not meeting the required certifications; violation of operational rules
	Errors	**Applicable**. Error in assessing and responding to in-flight situations, which led the pilot to lose control of the aircraft
Level 2 Preconditions for Unsafe Acts	*Personal Factors / Operator Conditions*	**Applicable**. Extended wakefulness and pilot fatigue
	Environmental Factors	**Applicable**. Adverse meteorological conditions; spatial disorientation
Level 3 Unsafe Supervision	*Inadequate Supervision / Inappropriate Operational Planning / Supervisory Violations*	**Applicable**. Training records contained omissions and lacked clarity regarding how the operator addressed the pilot's deficiencies observed during evaluations
Level 4 Organizational Influences	*Organizational Climate / Organizational Processes*	**Applicable**. A culture of complacency regarding the use of the aircraft for non-scheduled public transport without proper licensing; the company frequently summoned the crew without adequate lead time, hindering proper mission planning and potentially contributing to pilot fatigue and a perceived urgency to complete missions

The Bowtie diagram presents the analysis of the threats, barriers and consequences related to the loss of control over the helicopter (Figure 1). The pilot's lack of knowledge or experience can be inferred from the inadequate performance during assessments. Such deficiencies should have been addressed through training; however, the training provided was inadequate, given that assessments and observations were not properly recorded, thus hindering corrective actions to resolve the pilot's identified shortcomings. Pilot fatigue and the limited time available for planning could have been mitigated through appropriate crew scheduling. Additionally, the company's organizational procedures proved inadequate, and supervision of scheduling practices appeared to be nonexistent.

These latent conditions and the absence of effective barriers, occurring in a permissive environment and with a newly hired pilot who was possibly feeling pressured to fly (due to the factors described in the previous analysis), contributed to an Unintended IMC (UIMC) situation, which resulted in a loss of control of the helicopter (top event).

On the right side of the diagram, the emergency procedures were faulty, and the use of incorrect equipment for orientation, ignoring the helicopter instruments, represented breaking the last barriers to mitigate the consequences of the accident, that resulted in four fatalities and the total destruction of the helicopter. There was no mention to an evacuation plan to the nearest hospital, but all occupants were fatally wounded at the moment of the crash, so even an effective plan of evacuation would not have avoided the human losses.

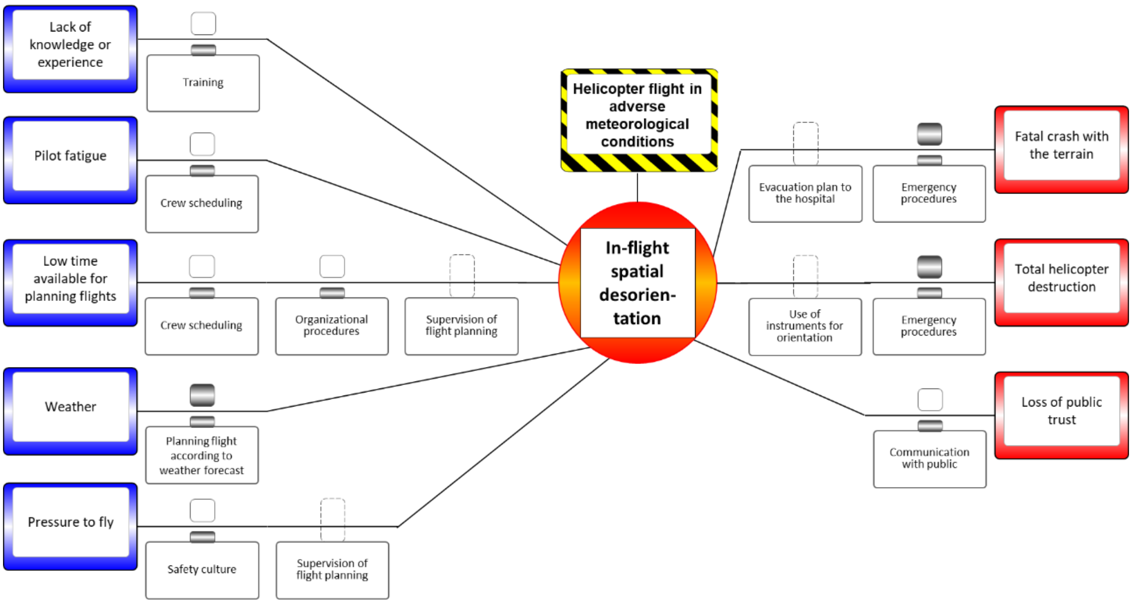

Figure 1: Bowtie diagram for losing control over the helicopter in Final Report A-157/CENIPA/2016.

3.2. Final Report NTSB/AAR-21/01

On January 26, 2020, at approximately 09:07 local time, a Sikorsky S-76B helicopter operated by Island Express Helicopters departed from John Wayne Airport (SNA) in Santa Ana, California, heading to Camarillo Airport (CMA) in Camarillo, California. The aircraft was carrying one pilot and eight passengers.

During the flight, the helicopter encountered adverse weather conditions, including dense fog and low cloud ceilings, resulting in significantly reduced visibility. Despite these conditions, the pilot chose to proceed under visual flight rules (VFR). As the flight progressed, the aircraft inadvertently entered instrument meteorological conditions (IMC), even though neither the pilot held an instrument rating nor was the helicopter certified for instrument flight operations.

According to the official report, the pilot experienced spatial disorientation and judgment errors. Furthermore, the aircraft was not equipped with critical technological safety barriers, such as a Terrain Awareness and Warning System (TAWS). This sequence of events culminated approximately 40 minutes after takeoff, when the helicopter impacted terrain during a steep descent in Calabasas, California. The aircraft was destroyed, and all occupants sustained fatal injuries.

The analysis based on the HFACS, as outlined in Table 2, identified failures at multiple levels. At the level of Unsafe Acts, the decision to continue the flight in deteriorating weather conditions represented a violation of operational protocols and disregarded guidance on avoiding inadvertent entry into IMC. At the level of Preconditions for Unsafe Acts, the investigation highlighted that the pilot experienced spatial disorientation after losing external visual references, likely exacerbated by vestibular illusions. At the level of Unsafe Supervision, the report pointed to deficiencies in the implementation of the operator's Safety Management System (SMS), particularly the lack of effective mechanisms to monitor and evaluate risk assessment forms completed by pilots.

The investigation found no evidence of direct pressure from the operator or client to conduct the flight. In fact, the company had a clearly defined policy to suspend flights in adverse weather and resume only once conditions improved. However, the report emphasized the role of self-imposed pressure as a key factor in the pilot's poor decision-making. It is noteworthy that the pilot regularly transported the principal passenger, basketball player Kobe Bryant, and had developed a personal friendship with him. Thus, the continuation of the flight despite worsening weather was attributed to a combination of the pilot's desire to meet the client's expectations, the absence of a viable alternate plan, and a growing continuation bias as the aircraft neared its destination. Additionally, reports indicated that the main passenger specifically requested this pilot for his flights, which may have further reinforced a sense of personal commitment, prompting the pilot to persist in completing the mission.

Therefore, although the pressure was neither institutional nor explicitly imposed, the operational environment and interpersonal relationships created favorable conditions for the emergence of psychological self-imposed pressure. This latent factor, when combined with organizational shortcomings and flawed individual decisions, contributed significantly to the tragic outcome of the flight.

Table 2: HFACS analysis for Final Report NTSB/AAR-21/01.

HFACS Level	Category	Classification Based on the Report
Level 1: Unsafe Acts	*Violations*	**Applicable**. Decision to continue the flight in IMC conditions, despite the aircraft and the pilot not meeting the required qualifications for this type of operation; violation of operational rules
	Errors	**Applicable**. Error in assessing and responding to flight situations, leading to loss of control of the aircraft
Level 2: Preconditions for Unsafe Acts	*Personal Factors / Operator Conditions*	**Not Applicable**. Pilot's medical, psychological, and rest conditions were considered adequate.
	Environmental Factors	**Applicable**. Adverse weather conditions; spatial disorientation
Level 3: Unsafe Supervision	*Inadequate Supervision / Inappropriate Operational Planning / Supervisory Violations*	**Applicable**. Lack of supervision regarding the planning of the flight under unfavorable weather conditions
Level 4: Organizational Influences	*Organizational Climate / Organizational Processes*	**Applicable**. The close relationship between the pilot and the passenger contributed to a personal sense of commitment to complete the flight

The Bow-Tie diagram shows that some threats, such as outdated FRAT (Flight Risk Assessment Tool), self-imposed pressure, and added workload from ATC (Air Traffic Control) calls and the transponder IDENT (identity button), converged on the top event: spatial disorientation and loss of control. Preventive barriers failed, were inadequate or missing. The helicopter entered IMC, the pilot became disoriented, and a rapid descent began. Mitigating barriers failed, and consequently the aircraft struck the ground at high speed, causing nine fatalities, and total loss of the helicopter.

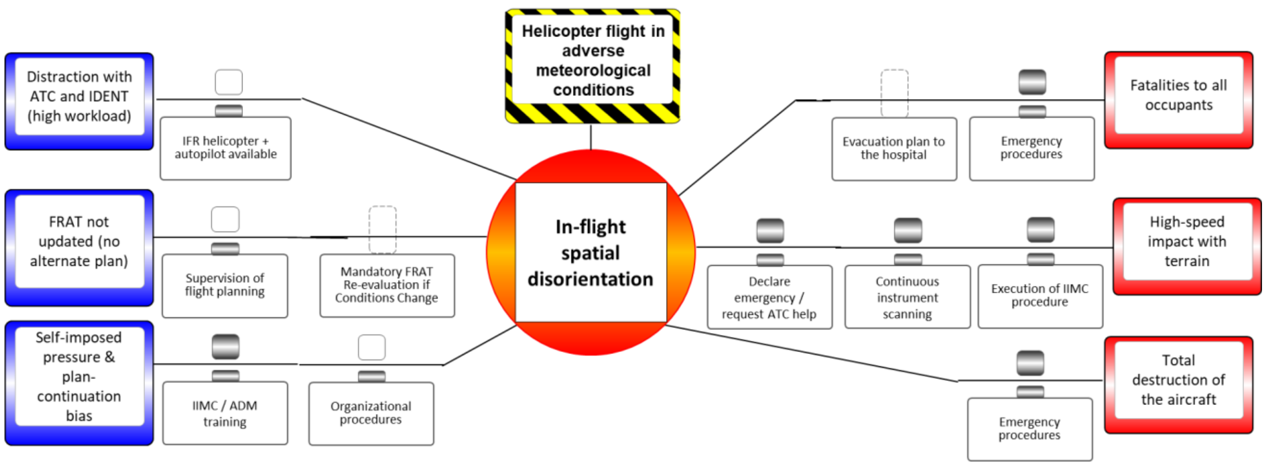

Figure 2: Bowtie diagram for Final Report NTSB/AAR-21/01.

3.3. Helicopter Accident Number 3

To preserve anonymity and confidentiality, specific details of this accident have been withheld, and only aspects relevant to the analysis are discussed. The event involved a helicopter crash occurring in a forested region during a rescue mission. The aircraft entered dense cloud formations, lost control, crashed, and was destroyed, resulting in fatalities. The HFACS analysis identified that operational pressure related to Organizational Influences significantly contributed to the accident, as mission accomplishment was prioritized, prompting the crew to disregard weather-related risks. Furthermore, the crew was accustomed to operating under adverse weather conditions, which increased their confidence to initiate the mission despite being aware of hazardous formations along the route. Unsafe Supervision contributed to the lack of measures inhibiting the flight in such climatic conditions. Regarding Unsafe Acts, the crew improperly utilized the weather radar to navigate through and avoid cloud formations, a practice recognized as incorrect, as elaborated subsequently. The corresponding Bowtie diagram is shown in Figure 3, evidencing the barriers that failed, were missing or inadequate.

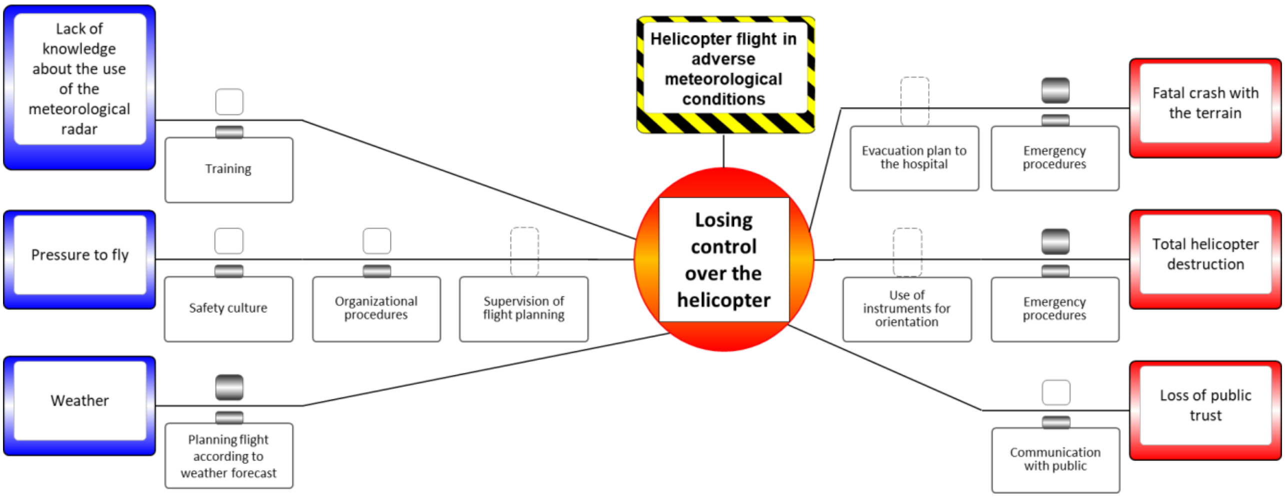

Figure 3: Bowtie diagram for Accident Number 4.

3.4. Discussion on the Accident Analyses

Pressure to perform missions typically emerges at the Organizational Influences level in HFACS. Factors associated with decision-making and perceptual errors belong to the Unsafe Acts level, underscoring the need for integrated training and reinforced operator capabilities. Enhancing basic training and adherence to aircraft operational constraints and crew competencies could prevent repeated dangerous decisions during flight planning and execution. Such shortcomings led crews to falsely perceive a safe operational margin. Scenarios wherein pilots progressively descend to avoid adverse weather, until they cannot avoid the clouds anymore and visual references are lost (resulting in spatial disorientation within clouds) can be preemptively mitigated through appropriate training and awareness measures. Among conditions observed in the three accidents studied, improper use and inadequate understanding of meteorological radar proved particularly hazardous, even for experienced pilots, and will thus be examined in further detail below.

3.5. Meteorological Radar

Meteorological radar emits radio waves, typically X-band frequencies in modern systems, that reflect off weather phenomena and return to antennas. The reflected data is then displayed inside the cockpit, using a color gradient from green to red. The radar display colors correspond to reflectivity rather than directly indicating hazard severity. Certain high-risk conditions, such as dry ice at the upper portion of cumulonimbus (CB) clouds, exhibit low reflectivity and appear green despite their danger. Although, directing the radar to a lower position can reveal yellow and red regions some thousand feet below the route, indicating a dangerous region ahead (just above a CB). Consequently, this radar characteristic knowledge, followed by continuous adjustments of radar tilt, range, and gain during flight are essential for accurate situational awareness.

Regions with high-density cloud formations may absorb radar waves, creating shadow zones that falsely suggest open "corridors" or clear paths ahead. Thus, meteorological radar should strictly be utilized to avoid formations rather than navigate between them, preventing false corridor interpretations. Figure 4 illustrates an example of such a false corridor impression (left image), contrasted with adjusted range settings revealing a central cloud formation (right image). A pilot relying solely on initial radar indications, and using it for the wrong purposes (overestimating meteorological radar capabilities and ignoring their intrinsic limitations), would inadvertently direct the aircraft into the center of a larger, hidden formation.

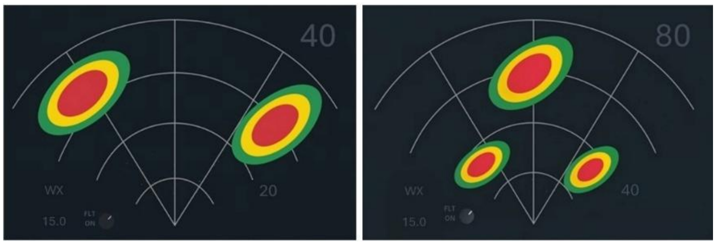

Figure 4: False corridor impression due to the use of the wrong range (on the left), in contrast to the use of a further range (on the right) for the meteorological radar.

4 CONCLUSIONS

The HFACS analysis of the accidents systematically identified pressures to fly under degraded weather conditions, consistently categorized at level 4 (Organizational Influences). These pressures encompassed implicit institutional and self-imposed factors often associated with pilot-passenger dynamics, organizational cultures emphasizing punctuality, or critical mission urgencies, notably in the case of the rescue operation. These pressures were exacerbated by pilot inexperience, which impaired effective risk perception, and are consistent with aviation safety literature. At level 3 (Unsafe Supervision), deficiencies in operational oversight mechanisms were identified, failing to prevent flights from initiating or continuing despite deteriorating weather. Level 2 (Preconditions for Unsafe Acts) highlighted contributing factors such as pilot fatigue, inadequate rest, gaps in training, and insufficient psychological preparedness to handle critical decisions under stress. At level 1 (Unsafe Acts), operational violations were observed, including unauthorized entry into Instrument Meteorological Conditions (IMC), errors in judgment, poor situational awareness, and spatial disorientation.

The Bowtie diagrams illustrated latent conditions that existed prior to the accidents, which could have been mitigated by barriers that ultimately failed, were absent, or inadequate. Once the top event occurred, limited time for an effective response and inadequacies in mitigation barriers (on the diagram's right side) contributed to the fatalities.

The combined analysis revealed that whereas pressures were a determining factor (organizational and self-imposed), they did not fully explain the pilots' decision to continue flying, which was fundamentally sustained by overconfidence, misuse of onboard instruments, incorrect interpretation of instrument data, or misconceptions about avionics functions, stemming from insufficient training, experience, and knowledge of adverse weather flight conditions. Particular attention should be directed toward the correct application and intended usage of weather radar systems, given their complexities and the requirement for comprehensive training.

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