CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Transportation Sciences

Department of Air Transport

FRAM Analysis of Aircraft Accidents With Respect to Flight Procedures

Bachelor thesis

Study Programme: Technology in Transportation and Telecommunications

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Thesis Supervisor: doc. Ing. Andrej Lališ, Ph.D.

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BACHELOR'S THESIS ASSIGNMENT

(PROJECT, WORK OF ART)

Student's name and surname (including degrees):

Jiaxing Wang

Study programme (field/specialization) of the student:

bachelor's degree – LED – Air Transport

Theme title (in Czech): **Realizace metody FRAM v šetření leteckých nehod s propojením na letové procedury**

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Guidelines for elaboration

During the elaboration of the bachelor's thesis follow the outline below:

- Thesis goal: Identification of relationship between flight procedures and FRAM analysis of selected aircraft accidents
- Analyze FRAM method for aircraft accident investigation
- Select and analyze patricular aircraft accidents and identify relevant flight procedures
- Perform FRAM analysis for the selected accidents and determine the relevance of flight procedures in the analysis
- Evaluate the achieved results

Graphical work range: according to the instructions of thesis supervisor

Accompanying report length: minimum of 35 text pages (including figures, graphs and sheets which are part of the main text)

Bibliography:

Allweyer, T. BPMN 2.0: Introduction to the Standard for Business Process Modeling. 2nd Ed, Books on Demand 2016.

Hollnagel, E. FRAM, the Functional Resonance Analysis Method: Modelling Complex Socio-technical Systems, 2012.

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Date of bachelor's thesis assignment: **October 8, 2020**
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Date of bachelor's thesis submission: **December 1, 2021**
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b) in case of postponing the submission of the thesis, next submission date results from the recommended time schedule

L. S.

doc. Ing. Jakub Kraus, Ph.D.
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doc. Ing. Pavel Hrubeš, Ph.D.
dean of the faculty

I confirm assumption of bachelor's thesis assignment.

Jiaxing Wang
Student's name and signature

Prague ....August 13, 2021

Declaration

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Date: 1.12.2021

Jiaxing Wang

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Abstrakt

Cílem této bakalářské práce je využití metody FRAM pro analýzu nehod a propojení s letovými postupy. První kapitola představuje princip fungování metody FRAM a související literaturu. Na základě čtyř kroků metody FRAM tato práce analyzuje pět nehod/incidentů vybraného typu letounu Piper PA44 a propojuje analýzu s letovými postupy. Práce ve svém závěru stanovuje, že pokud letový postup má přímý nebo nepřímý vliv na nehodu, lze variabilitu v nehodě utlumit úpravou a doplněním letového postupu.

Klíčová slova

Metoda funkční rezonanční analýzy, funkční rezonance, letový postup, Piper PA-44, analýza nehod

Abstract

The objective of this bachelor thesis is to use the FRAM method for accident analysis and to link to flight procedures. The first chapter introduces the working principle of FRAM method and related literatures. Based on the four steps of the FRAM method, this paper analyzes the five accidents/incidents of the selected model Piper PA44 and links the analysis to the flight procedures. The thesis suggests when the flight procedure directly or indirectly affects the accident, the variability in the accident can be damped by modifying and supplementing the flight procedure.

Keywords

Functional Resonance Analysis Method, functional resonance, flight procedure, Piper PA-44, accident analysis

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Introduction

One of the goals of accident analysis is to analyze and determine what causes the event to lead to unexpected results, and to learn from it or find solutions to reduce risks in the future. However, simply enumerating the contributing factors of the accident cannot effectively discover the cause of the problem. And in many fields, including aviation, the existing systems are very complex. At this time, some analysis models are needed to complete the systematic way. At present, there are mainly three types of recognized accident models: causal sequence models represented by the domino model, epidemiological models such as the Swiss cheese model, and systemic models such as FRAM (Functional Resonance Analysis Method) and STAMP (Systems-Theoretic Accident Model and Processes).[7] The FRAM describes a complex system from a perspective of function, defines the couplings between functions, and defines the mutual influence of more than two variabilities as resonance. Using FRAM, analyst can analyze the cause of the accident through four steps and put forward safety recommendations.

Flight procedures are mainly divided into departure procedures, en-route procedures, arrival procedures and approach procedures. In reality, flight procedures are derived from the operation manual of the aircraft, the flight plan of the relevant airport, etc. Flight procedures directly affect the behavior of pilots, so relevant flight procedures should also be noted in the accident analysis.

This paper describes the principles of the FRAM model and documents FRAM analysis of five accidents/incidents on the selected aircraft -Piper PA44. In addition, FRAM functions are linked to flight procedures in accident analysis to explain the relevance between flight procedures and accident analysis.

1 Current state of the art

This chapter will introduce the flight procedures and the principle of FRAM, as well as the literatures on the application of FRAM to aviation accident analysis.

1.1 Flight procedures in the aviation

The following is a brief overview of departure procedures, en-route procedures, arrival procedures and approach procedures.

Standard Instrument Departure (SID) is a departure program typically developed to accommodate as many aircraft categories as possible. The standard design gradient for the departure procedure is 3.3%. A programmed gradient greater than 3.3% can be specified when there are obstacles affecting the route of departure. When such a gradient is specified, the altitude/height from which it extends is published. Wherever possible, a straight departure is specified. Straight deviation refers to the straight-line deviation within 15° of the alignment of the center line of the runway with the initial deviation track. When the starting route requires a turn of more than 15°, it is called a turning departure. Assume direct flight until an altitude/height of at least 120 m (394 ft) is reached. Procedures normally call for turns at a point 600 m from the beginning of the runway However, in some cases the turn should not be initiated before the DER (Departure end of the runway), or the designated point, and this information will be indicated on the departure chart. The maximum speed used in the departure procedure shall be increased by 10% from the maximum speed of the final missed approach to account for the increase in the mass of the aircraft at take-off (see Fig. 1. Maximum speeds for turning departures) unless otherwise stated in the procedure.

Aeroplane category	*Maximum speed km/h (kt)*
A	225 (120)
B	305 (165)
C	490 (265)
D	540 (290)
E	560 (300)
H	165 (90)

Fig 1. Maximum speeds for turning departures (source: DOC8168)

If appropriate navigation AIDS (Airborne Integrated Data System) are not available, or track navigation is not provided, an omnidirectional procedure is used. If obstructions do not permit omnidirectional procedures, the pilot should ensure that the ceiling and visibility will permit obstacles to be avoided visually. Omnidirectional departure can specify sectors to avoid.

An en-route is a procedure that uses air route standards to assume that an aircraft can operate normally. It is important to note Obstacle Clearance Areas. Both primary and secondary zones are specified when defining obstacle clearance areas. These are defined in such a way as to ensure that the aircraft position will be contained within the primary area 95% of the time and within the secondary area 99.7% of the time. (See Fig.2 obstacle clearance areas)

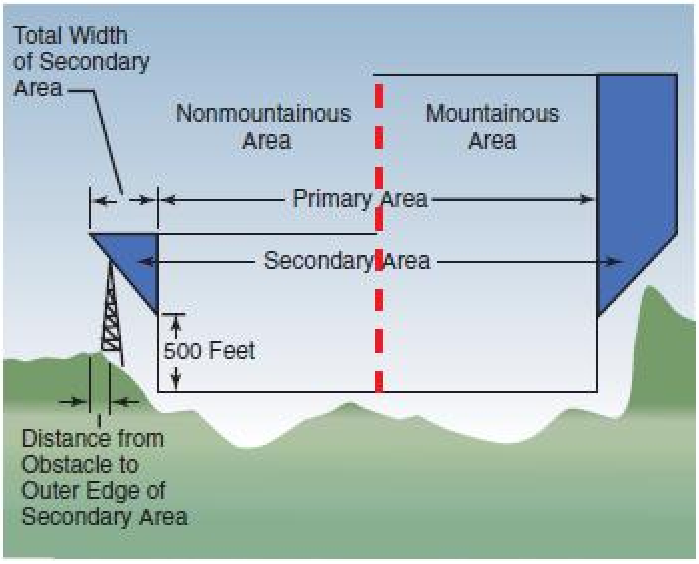

Fig.2 obstacle clearance areas (source: INSTRUMENT PROCEDURES HANDBOOK)

Performance-based Navigation (PBN) is applicable to the general standard for VHF omnidirectional radio range (VOR) and non-directional beacon (NDB) routing. Unless it is revised, the standard assumptions for developing route based PBN programs are:

A) the positioning tolerance range of waypoints is a circle whose radius is equal to the precision value of navigation specifications; and B) the navigation system provides information that the pilot monitors and uses to intervene to limit excursions outside the designed area.

The standard instrument arrival (STAR) route allows a transition from the en-route phase to the approach phase. The route of arrival from the en route phase to the fix or facility used in the program will be published when necessary or if an operational advantage is gained. Typically, this is initial approach fix (IAF). Given the minimum sector height (MSA), omnidirectional or sector access can be provided.

The conventional instrument approach procedure is based on the guidance provided by the ground system. For aircraft with a database of approach procedures, the pilot should verify that the correct procedures have been loaded into the navigation system by comparing it with the approach map before starting the approach. This inspection shall include a) sequence of navigation points; b) The rationality of the track and distance of the approach section, as well as the accuracy of the inbound course and the length of the final approach segment (FAS). Parts of the approach procedure: The instrument approach procedure may have five separate parts. They are the arrival, initial, intermediate, final and missed approach segments. In addition, an area for circling the aerodrome under visual conditions is also considered. The approach segments begin and end with the specified fix. However, in some cases, certain segments may start at a specified point where no fix is available. For example, a precise approach FAS can begin at the point where the intermediate flight altitude intersects the nominal glide path (the final approach point).

Type of approach: There are two types of approach. Straight-in and circling approach. Where possible, a straight approach aligned with the center line of the runway will be specified. Pilots should be aware that for imprecise approaches, a straight approach is considered acceptable if the final approach trajectory is at an Angle of 30° or less from the center line of the runway. In the case of terrain or other constraints, the circling approach will be used. The alignment or descent that leads to the final approach track exceeds the criteria for a direct approach. The final approach track of a circling approach procedure is in most cases aligned to pass over some portion of the usable landing surface of the aerodrome. [1]

1.2 FRAM safety method

This chapter explains the principles of FRAM, including method steps, functional representation and functional resonance.

1.2.1 Method steps

Step 1: Identify important system functions. Six basic parameters are used to characterize each function (see Figure 3).

Step 2: Describe the observed and potential system function variability associated with the environment. Consider the variability of normal and worst-case scenarios. The output of a function will be too early, on time, too late, or not generated at all, and may be accurate, acceptable, or inaccurate.[21]

Step 3: Identify and describe functional resonance from the observed dependence/coupling between functions and the observed variability. These functions can be connected through their aspects, which provide the basis for identifying how the functions are coupled. For example, the output of one function may be the input of another function, or produce resources, meet precondition, or enforce control or time constraints. If the output of one function is an unpredictable variable, another function that relies on that output as a resource may perform unpredictably. The occurrence and propagation of many such changes may produce resonance effects.[14]

Step 4: Identify control mechanisms or obstacles to variability (damping factors) and specify the required performance monitoring.[2] Four types of barrier systems have been identified: 1) physical barrier systems prevent the movement or transmission of mass, energy or information, 2) functional barrier systems set up prerequisites (by humans and/or machines) that need to be met before action, 3) Symbolic barrier systems indicate restrictions on existing actions, such as alarms 4) An invisible barrier system is an indication of restrictions on actions that do not exist.[3]

Each vertex of the hexagon has corresponding letters, which are T, C, O, R, P, I (T-time, C-Control, O-Output, R-Resource, P-precondition, I-input)., see Fig. 3 The six aspects of functions

The specific meaning of each letter and how to use it will be shown in the next section. In a complete model, there will be many different functions, each of which represents a different meaning. Function can be an action (turn off/on). The description of a function is an activity. However, ‘After turning off/on ’is a state. The State is displayed on the connection line of each function

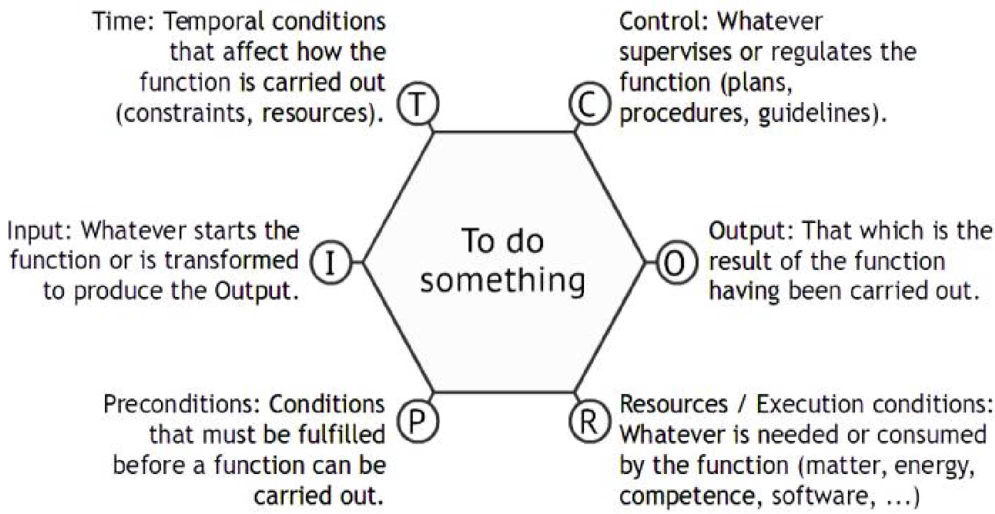

Fig. 3 The six aspects of functions [3]

1.2.2 Functional representation

The following are definitions of the six parameters. It is important to understand what this means before modelling.

Input (I): Used or converted by the function.

Output (O): The output is produced by the function.

Precondition (P): Refers to the conditions that must be met before the function is executed.

Resource (R): Resources are needed or consumed when a function is executed.

Control (C): Control is supervision, regulation or monitoring.

Time (T): Affects time availability, such as duration and starting point.

The first is O-output. Except for the last one, each function needs output to connect the next or the next stage of the function. Its description will vary depending on the function of the next stage, as well as the actual situation. The specific description can be understood in the following explanation of the other three functions. I-input, the simplest relational Input description, is a continuation of an event/action.

For example, the connection object for two functions is Instruction. Therefore, instruction is added in the O description of A (ATC instruction) and add instruction in the C (Pre-flight Inspection) description of B (take off). P-precondition, conditions that must be fulfilled to perform a function. The requirements of C (Pre-flight Inspection) need to be met before A (ATC instruction) is executed. See, Fig. 4.

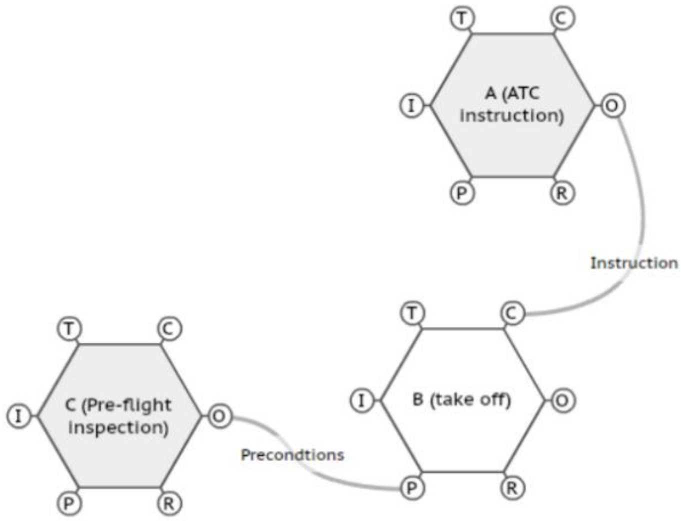

Fig. 4 Practical Example

1.2.3 Functional resonance

Functional resonance is closely related to the variability of functions. In FRAM, the variability of two or more functions can coincide and decay or amplify each other. The variability of one function affects the variability of others in a way that is manifested by functional resonance. Functional resonance offers a systematic way to understand outcomes that are both non-linear(emergent), and non-causal (disproportionate).[3] So, what is functional variability? There are many forms of variability: 1) availability of personnel and equipment, 2) training, preparation, competence, 3) communication quality, 4) human-machine interaction, operational support, 5) availability of procedures, 6) work conditions, 7) goals, number and conflicts, 8) available time, 9) circadian rhythm, stress, 10) team collaboration, and 11) organizational quality.[4] The variability needs to be determined qualitatively in terms of stability, predictability, adequacy and performance boundaries.[6]

1.3 Literature review (FRAM papers - accidents investigation)

FRAM is used in the aviation industry. In order to better carry out the research, I found and analyzed 11 papers that applied FRAM to accidents in aviation field. The article 'Using the Functional Resonance Analysis Method (FRAM) in Aviation Safety: A Systematic Review' [21] counts the papers that have used FRAM to analyze accidents in recent years.

Analysis of Comair flight 5191 with the Functional resonance accident model [5]

This paper introduces the principles of FRAM and shows how FRAM can be used to analyse the highly publicized crash of Comair Flight 5191 in Lexington, Ky., on August 27, 2006. Procedures include review of weather and airport data, taxi briefing, take-off briefing, ATC clearance, execution of taxiing checklist, taxi to runway operation, execution of pre-take off checklist, turn to runway, take-off.

Comparing a multi-linear (STEP) and systemic (FRAM) method for accident analysis [6]

Sequential Timed Event Mapping (STEP) and Functional Resonance Analysis (FRAM) methods for event analysis and modelling are compared in this paper. The main problem to be solved in this paper is to compare the established multilinear method (STEP) with the systemic method (FRAM) and to evaluate what new insights the latter systemic method provides for accident analysis compared with the previously established multilinear method. The communication between the TWR, APP, ground equipment and the pilot during the approach is described in FRAM. Procedures include transmitting radio communications, change APP frequency to TWR frequency, receiving radio communications, Gardermoen TWR control, auto-pilot approach, manual approach, etc.

Extended FRAM by integrating with model checking to effectively explore hazard evolution [7]

The author proposes that because FRAM is generally regarded as a theoretical method, it lacks specific methods or supporting tools to link theory with practice. In order to fill the gap and contribute to the development of FRAM, (1) function's variability was described further, with the rules of interaction among variability of different functions being determined, and (2) the technology of model checking (MC) was used for the analysis of function's variability to automatically search the potential paths that could lead to hazards. The MC can simulate the behaviour of the system (normal or abnormal) and provide counterexamples (if any) that violate the safety constraints and requirements to improve the system design. In this paper, FRAM was enhanced to explore the paths of hazard evolution by integrating with model checking. Directing two aircraft to take off at the same time is described in FRAM. Procedure for flight 686 includes the air traffic controller guidance flight 686 to R6 runway, taxiing to R6 runway, ATC guidance and take-off. Procedures for business jet include ATC guided business jet to R5 runway, reported to ATC in the S4 taxiway position, ATC confirmed position, ATC guided business jet continue to slide to the main runway, turned left into the R6 runway.

FRAM for systemic accident analysis (a matrix representation of functional resonance) [8]

This paper aims to enhance the strength of FRAM-based accident analysis and discusses the Resilience Analysis Matrix (RAM), a user-friendly tool that supports analysts during the analysis process to reduce the complexity of FRAM representation. RAM provides a two-dimensional representation, highlighting the system connection between the couplings, thereby highlighting the high connection between the couplings. In this paper, a systematic accident analysis was conducted by FRAM on the runway incursion incident at Los Angeles International Airport in February 1991, involving SkyWest Flight 5569 and USAir Flight 1493. There is a complex FRAM model that includes 59 functions. The main types of the functions are involved in ATCO, pilot, organization/pilot, organization airport, organization/ATCO, technology/pilot, technology/ATCO. For example, give a take-off clearance, make a taxi briefing, observe weather phenomenon, etc.

Improvisation at Workplace and Accident Causation (an exploratory study) [9]

This article introduces the application of FRAM in the exploratory study of workplace accidents, aiming to better understand the accidents caused by improvisation at work. Three accident reports were selected from Brazil's open database and introduced to outline the role of improvisation at work on accident causation. The first accident took place in an aircraft maintenance company with more than 100 employees. In order to study the accidents caused by improvisation, this research applied FRAM. What all these cases have in common is the lack of awareness of the hazards, the lack of planning, the lack of supervision, and the pressure exerted by productivity companies on workers. They are Workers falling from unsafe stair models, Workers need to discharge when operating the concrete mixer model and Worker suffered burns and tried to clean her workbench model. Procedures include pressure to install target system faster, pick up the matching dock station ladder, make ladder available, position the ladder on the dock station, pick up the blueprint, access the dock station, accident.

Resilience assessment based on models of functional resonance [10]

This paper explores the five key resilience characteristics of FRAM (buffering capacity, flexibility, margin, tolerance, and potential for cross-scale interaction). In addition, FRAM-based resilience assessment challenges the description and definition of these characteristics and raises some specific questions that can further develop its assessment. There are functions that describe the system behaviour that was designed/regulated and executed over a long period of time (from the design of the MD-83 or DC-9 in the 1960s to the collapse in 2000). "Alaska261 Elasticity Evaluation Model" Procedure include end-play checking, Jackscrew lubrication, Jackscrew movement, horizontal stabilizer movement, FAA oversight.

Safety analysis of aviation flight deck procedures using systemic accident model [11]

This paper studies the use of FRAM to check the safety management of flight deck procedures. In this article, an adaptive cognitive reliability and error analysis method (CREAM) is mentioned for systematic and quantitative FRAM analysis. This paper applies the proposed method to the actual air crash near Cali Airport. And concluded that the accident was caused by deviation from standard operating procedures. Based on the author's analysis, it is found that FRAM can identify potentially dangerous paths that may lead to accidents. The author also proposed a new method, using the framework to pre-analyze the safety of the design program. FRAM is used to describe which Common Performance Conditions (CPCs) in the function are affected by variability. It is about model of approach preparation. Procedure include communication with ATC, input and execute the route to FMC, identifying approach course, descending for new approach course, review of flight plan for RWY change.

Safety Analysis of Systemic Accidents Triggered by Performance Deviation [12]

Autopilot has made a great contribution to reducing the workload of aviation people, but it may cause new types of aircraft accidents, namely automation caused accidents. This paper proposes a systematic method to solve this problem from the perspective of safety management. The author uses FRAM to find possible collapses in a series of operating procedures due to changes in cockpit conditions. It analyzes how the performance deviation in a specific operation affects other operations, and when and where the expected situation collapses due to the non-linear interaction of multiple performance influencing factors. Normal procedure model (Cockpit Voice Recorder recorded) is described in FRAM. The Functions include: (A) Monitoring the instrument (B) Confirmation of the passage of VOR (C) Communication with ATC (D) Checking the flight path using the chart (E) Inputs of flight path information to CDU and their execution (F) Keeping the fight path (G) Arrival at the correct navigation beacon (H) Maneuvering instruments for landing.

The Alaska Airlines Flight 261 accident (a systemic analysis of functional resonance) [13]

On January 31, 2000, on Alaska Airlines Flight 261, an MD-83 crashed into the Pacific Ocean; due to the failure of the top nut of the jack assembly of the horizontal stabilizer trim system during flight, the aircraft pitch control was lost (NTSB, 2003). This paper treats each of the steps of analysis according to FRAM and discusses how functional resonance occurred through the variability in functions performed by joint human, technical, and organizational systems. Procedure includes end-play checking, Jackscrew up-down movement, lubrication, Jackscrew replacement, horizontal stabilizer movement, limiting stabilizer movement, aircraft pitch control.

The use of Functional Resonance Analysis Method (FRAM) in a mid-air collision to understand some characteristics of air traffic management system resilience [2]

The author used FRAM in the air collision of commercial aircraft Boeing 737-800 flight GLO1907 and EMBRAER E-145 executive jet N600XL to study the key resilience characteristics of the air traffic management system (ATM). The accident occurred at 4:56 pm Brazil time on September 29, 2006, in the clear Amazonian sky. FRAM analysis of flight monitoring functions showed environmental constraints (equipment, training, time, supervision) that produce variability in system behavior, creating demand resources mismatches in the attempt to perceive and control the developing situation. This variability also includes control and coordination failures and automation accidents (TCAS operation). The analysis shows that under normal variability conditions (no catastrophic failure), ATM systems (pilots, controllers, supervisors, equipment) couldn't use feedback or feedforward strategies to close the control loop of the flight monitoring function, thus failing to control the aircraft. 'Essential takeoff functions' and 'Essential functions of flying in RVSM' are described in FRAM. The procedures include flight preparation, flight plan elaboration, flight plan approval, ATC clearance, flight plan used. 'Essential takeoff functions' and 'Essential functions of flying in RVSM' are described in FRAM. The procedure of the second FRAM model includes TCAS in operation, fly in RVSM, ATC airspace monitoring, ATC communication.

Introduction of the concept of functional resonance in the analysis of a near accident in aviation [14]

This paper mainly describes how to describe a complex incident and automatically generated visualization by FRAM Visualizer. During a commercial flight to Paris-Orly, the

Captain decided to perform an automatic landing due to the weather conditions at destination. Since the First Officer was not qualified for this procedure, the captain took over most of the crew actions. On approach, he selected a wrong approach track on the HSI. Due to this error, the autopilot did not intercept the landing track (localizer), and the aircraft departed from the published trajectory. The captain tried to recover from this situation by selecting, unsuccessfully, various modes on the auto-pilot. The aircraft crossed the glide path and twenty seconds later, the captain corrected the selection of the track on the HSI. At the same time, he put the aircraft into descent, heading simultaneously towards the approach track. The autopilot was not able to capture the glide path, so that the aircraft continued its descent without external references. The captain did not manage to stabilize his approach, and eventually initiated a go-around. The lowest height reached by the aircraft was 67 feet from the ground.

1.4 Examples of FRAM application

This chapter shows two practical examples of FRAM application from aviation. The first is application of FRAM to NAX541.

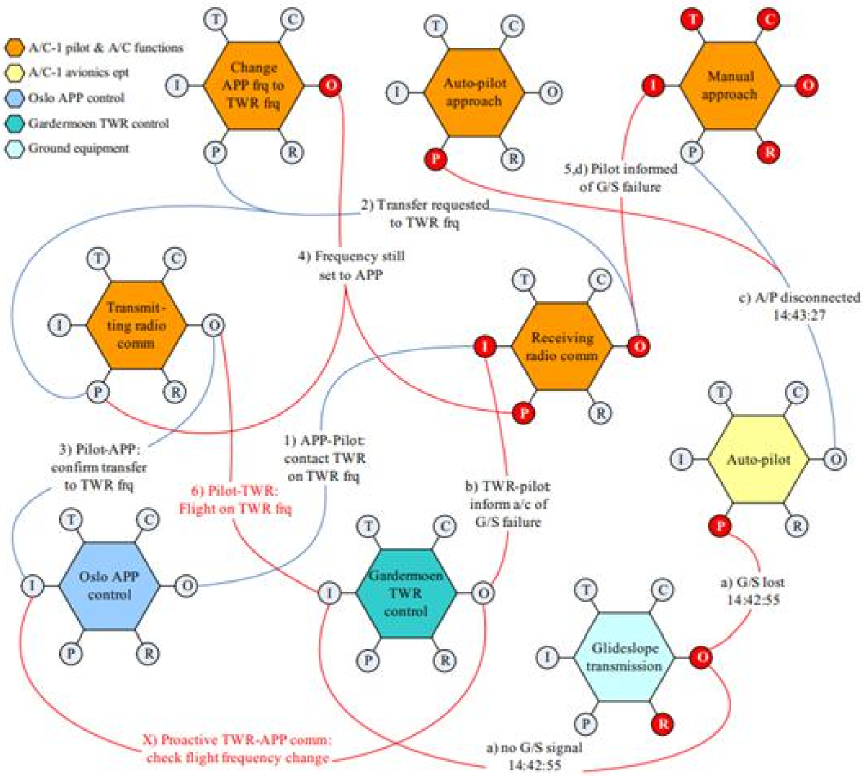

Fig 5. A FRAM instantiation during the time interval 14:42:37–14:43:27[6]

The authors divide functions into five categories, namely 'A/C-1 pilot & A/C functions', including transmitting radio communications, change APP FRQ to TWR FRQ, receiving radio communications, auto-pilot approach, manual approach; 'A/C-1 Avionics EPT 'Autopilot; 'A/C-1 Avionics EPT' -Autopilot; 'Oslo APP control'; 'Gardermoen TWR control'; 'Ground equipment' - Glideslope transmission. And used different colors to color the corresponding categories. Here I want to explain the changing of radio frequency. The entire airspace and all airports are divided into ATC areas of responsibility. Whenever a flight moves from one area of responsibility to another, the pilot needs to change frequency to talk to the next controller. A flight can only be under the control of one single ATC unit at any time, which usually equates to being on one single radio frequency. When under ATC control, pilots do not change frequencies unless instructed to do so. For the en-route phase, airspace is divided into sectors, defined as three dimensional areas. Each sector will typically have its own dedicated frequency, although sectors can be combined in which case several sectors may operate on the same frequency.

The analysis of accidents that occur during a flight phase of an aircraft is common. But the following example links the flight records of two aircraft together. They are Flight 686 and another business jet flight.[7] On 8 October 2001, an aircraft crashed at the Linate Airport in Milan, Italy. Scandinavian Airlines Flight 686 carrying 110 people collided with a Cessna Citation CJ2 business jet carrying four people. See, Fig.6 the instantiation of the functional interactions.

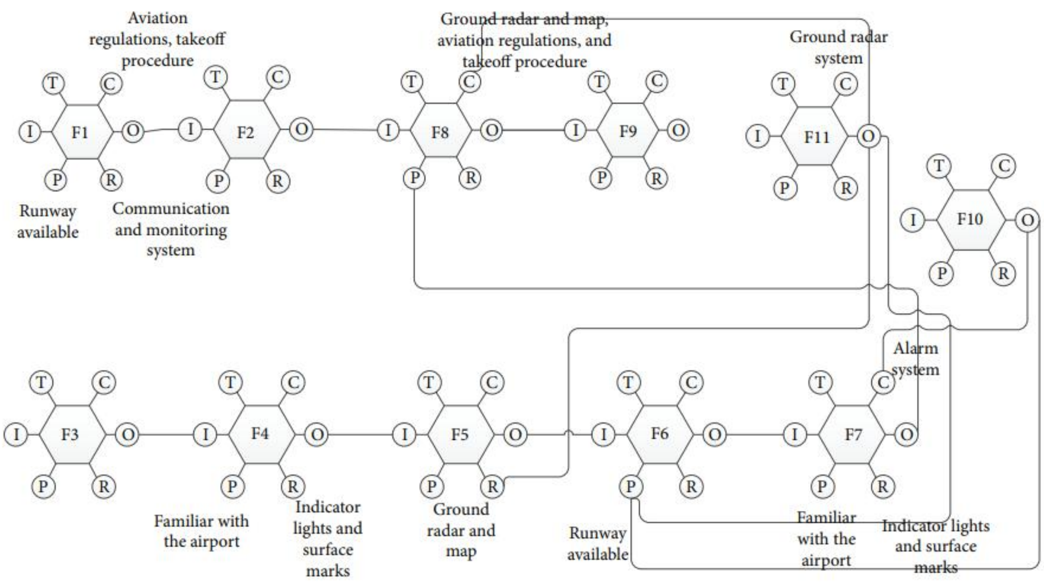

Fig.6 The instantiation of the functional interactions [7]

Airplane	Number	Function
Flight 686	Function 1	The air traffic controller guided flight 686 to R6 runway
	Function 2	Flight 686 taxied to R6 runway
	Function 3	ATC guided the 686 flight take off
	Function 4	Flight 686 took off
Business jet	Function 5	ATC guided business jet to R5 runway
	Function 6	Business jet reported to ATC in the S4 taxiway position
	Function 7	ATC confirmed business jet position
	Function 8	ATC guided business jet continue to slide to the main runway
	Function 9	Business jet turned left into the R6 runway

Fig.7 The functions of the flight 686 and the business jet flight [7]

Aspects	Variability	Influence on Output
Input	The order by ATC is imprecise	The plane takes the wrong runway
	The order is earlier	The plane takes the wrong runway earlier
	The order is later	The plane takes the wrong runway later
Precondition	The runway is not available	The plane shares the runway with other aircrafts
	The airplane does not fulfill ATC's taxi instructions	The plane takes the wrong runway
Resource	The crew members are not familiar with the airport situations	The plane takes the wrong runway
	The signal lights and the ground markings on airport are misleading	The plane takes the wrong runway
Control	Alarm system does not work properly	The plane is not prevented from breaking into the wrong runway
Time	Too short	The plane takes the wrong runway earlier
	Too long	The plane takes the wrong runway later

Fig. 8 Potential variability of function 7 [7]

By linking the flight data of the two flights, the process of the whole incident is obvious. Using FRAM, the relationship between the two aircraft and the ground and ATC is clearly described. This expanded and enriched the scope of the investigation.

1.5 Limitations of the current state

At present, there are three categories of accident models widely acknowledged: the causal sequence models represented by the domino model, the epidemiological models like the Swiss cheese model, and the systematic models such as FRAM, and STAMP (Systems-Theoretic Accident Model and Processes).[7] The reason why there is more than one model that has been used in aviation is because each model has its own advantages and disadvantages. As I. A. Herrera and R. Woltjer said, the STEP (Sequentially Timed Events Plotting) diagram focuses on events and does not describe the systems aspects: the understanding of underlying systemic factors affecting performance is left to experts' interpretation. FRAM enables analysts to model these systemic factors explicitly.

I think the function of FRAM can be appropriately added so that it can also show events at the same time or combines FRAM with other models in some form. For example, adding a parallel schema (or even hidden) to the FRAM model describes the entire event process in a way similar to the STEP principle. In this way, the analyst can provide assistance during the analysis, and the whole process of the incident can be seen more completely. Then the description of FRAM's non-linear dependence, performance conditions, variability and its functional resonance can be perfected.

Lastly, there is no research that can clarify the connection between FRAM and flight procedures. I want to find practical ways to use FRAM in aviation by linking FRAM analysis to flight procedures.

2 FRAM analysis of the accidents and incidents

The following is FRAM analysis of 5 accidents or incidents of Piper PA44-180 Seminole. The content includes accident related flight procedures and the links between flight procedures and FRAM analysis results. The 5 incidents/accidents were found in the database of Aviation Safety Reporting System[1]. The search criteria is only the selected aircraft model Piper PA44. In order to further understand the origin of the incident/accident and collect more complete information, I searched for relevant information on the official website of the national aviation accident investigation unit where the accident occurred.

2.1. Introduction to selected aircraft and its flight procedures

Piper PA44-180 Seminole is an American twin-engine light aircraft manufactured by Piper Aviation. The aircraft is developed from the Piper PA-28 single-engine aircraft and is mainly used for multi-engine flight training. Table 1 is specification of PA44-180 Seminole.

The flight procedures for this aircraft can be found in Piper PA44-180 SEMINOLE INFORMATION MANUAL [16]. The flight procedure is divided into two parts: emergency procedure and general procedure. In the emergency procedures, you can find the operating procedures required in special unexpected situations, such as fire, electrical failure, manual extension of landing gear, etc., and related emergency procedures checklist. In the general procedures, you can find the operating procedures under normal circumstances, such as preparation, starting engine and takeoff, etc., and related normal procedures checklist. For example, the figures below are checklist of landing gear unsafe warnings and landing gear

[1] ASRS - Aviation Safety Reporting System (nasa.gov)

unsafe warnings in emergency procedures. When the pilot detects that the landing gear is malfunctioning, the pilot must first perform the checklist of landing gear unsafe warnings to find the specific malfunction location pointed to by lights of different colors. Then refer to the 'landing gear unsafe warnings' to operate.

Table 1. Specification of PA-180 Seminole [16]

Propeller	Hartzell Scimitar 2-blade Constant Speed | Full Feathering
Maximum speed	311 km/h
Stall speed (landing gear and flaps retracted)	91 km/h
Engine	2x Lycoming L/O 360 A1H6/ E1A6 Piston
Dimensions	Wingspan: 38 ft 6 in | 11.8 m Height: 8 ft 5 in | 2.6 m Length: 27 ft 7 in | 8.4 m

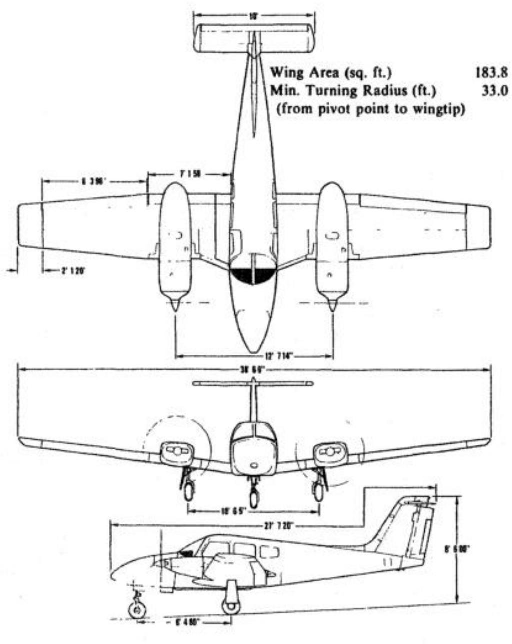

Fig 9. Three view of PA44-180 Seminole [16]

LANDING GEAR UNSAFE WARNINGS

Red light indicates gear intransit
Recycle gear if indication continues.
Light will illuminate and gear horn sounds when the gear is not down and locked if throttles are at low settings or wing flaps are in second or third notch position.

Fig 10. Checklist of landing gear unsafe warnings[16]

3.15 LANDING GEAR UNSAFE WARNINGS

The red landing gear light will illuminate when the landing gear is in transition between the full up position and the down and locked position. The pilot should recycle the landing gear if continued illumination of the light occurs. Additionally, the light will illuminate when the gear warning horn sounds. The gear warning horn will sound at low throttle settings if the gear is not down and locked, and when wing flaps are in the second or third notch position and the gear is not down and locked.

Fig 11. Emergency procedures - landing gear unsafe warning[16]

2.2. Kinglake VIC (Australia) accident

The aircraft was cruising, and the engine on the right began to run roughly. The pilot performed proper trouble checks but was unable to restore the full power of the engine. Since he believed that some power was being delivered, he did not turn off the correct engine. The pilot realized that the power output of the left engine was also insufficient. He was in the cloud and could not maintain his height. The pilot tried to turn to Lilydale Airport, which was closer than Essendon. While the plane was still over the Great Divide, the ground there was about 1,800 feet above the sea, and the plane descended from the cloud base. The pilot suddenly found himself about 35 feet above the trees, the ground was rising, and there were trees ahead. He successfully made a forced landing to the paddock on the sloping ground. [15]

The relevant emergency procedure related to this accident are Engine Failure During Flight and Air Start.[16]

2.2.1 Application of FRAM to Accident to Kinglake VIC

Step 1 is the identification and characterization of functions. A total of 11 functions were identified. All functions except ATC control will be performed by the pilot.

Table 2. List of functions of the FRAM model

Function	Agent
Cruising	Pilot
Continue to fly	Pilot
Perform proper trouble checks	Pilot
Shut down the right engine	Pilot
Air start	Pilot
Ensure the safety of the engine	Pilot
Keep the right engine turned on	Pilot
Attempt transfer to alternate airport	Pilot
Forced landing	Pilot
Landing at an alternate airport	Pilot
ATC control	ATCO

Step 2: Characterize the context-dependent variability of each node. For accident analysis, variability can be learned from survey data. In this case, the focus of the analysis is to compare observed and normal performance. For risk assessment, variability may originate from the characterization of common performance conditions (CPC), currently there are 11 in total. There are two variability in this accident analysis. The first variability is the failure of the aircraft's right engine during cruise. After the function ‘cruising’, if the two engines of the aircraft are operating normally, the aircraft can continue to perform the flight mission. But if the right engine of the airplane fails, the pilot will perform proper trouble checks. This variability belongs to the availability of equipment. In this accident, the pilot chose to make an emergency landing in a suitable area. The second variability is that after the "try to transfer to an alternate airport" function, insufficient height after the attempt to transfer exactly. It is necessary to decide whether to make an emergency landing based on the real-time altitude of the aircraft. If the altitude is satisfied, the aircraft can be landed at the alternate airport to avoid damage to the aircraft and ensure the safety of the people on board. If the altitude is not enough to support the aircraft to continue to transfer to the alternate airport, the aircraft should make an emergency landing on a suitable flat ground to reduce casualties. The second variability belongs to working conditions.

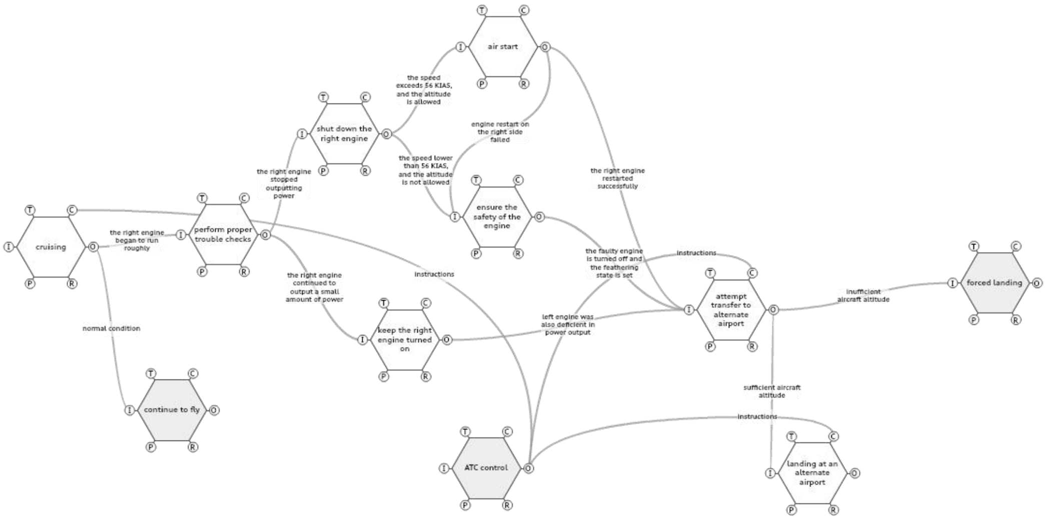

Fig 12. FRAM model of accident to Piper PA44-180 Seminole at Kinglake VIC

Step 3: Define functional resonance based on the possible dependence/coupling between functions and the potential for functional variability. There were no casualties in this incident and the aircraft landed smoothly, so it is not an accident. Therefore, no resonance is formed. But the first variability has an impact on the second variability. If the variability of the first one increases, the variability of the second one increases. For example, the failure of the right engine of an airplane to output power will cause the airplane to not have enough altitude to provide transfer to an alternate airport. Leading to an earlier forced landing of the aircraft, the short emergency response time may lead to more serious consequences. In this accident, the pilot found that the right engine was malfunctioning and thought it was still outputting power, so he did not turn off the malfunctioning engine. The pilot performed proper troubleshooting but was unable to restore the full power of the engine. Since he believed that some power was being delivered, he did not turn off the correct engine. The pilot realized that the power output of the left engine was also insufficient. After the left engine malfunctioned, the pilot immediately lost control of the altitude. The pilot tried to alternate airport Lilydale Airport. While the plane was still over the Great Divide, the ground there was about 1,800 feet above the sea, and the plane descended from the cloud base. Finally, the plane was forced to land in the plowed paddock during the transfer to the alternate airport.

Step 4: Determine the control mechanism or variability barrier (damping factor) and specify the required performance monitoring. Avoiding things from going bad is the main purpose of this step. Combining the cause of the accident and FRAM analysis, it is the key to ensure that the aircraft has sufficient altitude when a single engine fails. Because the aircraft loses the power of one engine, the aircraft's altitude will be lower as time goes by. This requires the addition of a function to monitor whether the faulty engine is suitable for restarting at the time interval between the start of a single engine failure of the aircraft and the time when the aircraft loses the opportunity to restart the failed engine. To help the pilot accurately judge the feasibility of restarting the malfunctioning engine and increase the possibility of a safe landing. It can be reflected in the FRAM model, adding a function after 'keep the right engine turned on'. It was input by 'left engine was also deficient in power output'. This can reduce the intensity of the second variability. Figure 13 is a possible practical example of this idea. The blue function is newly added. Although this may increase the complexity of the operation, it can effectively dampen the variability.

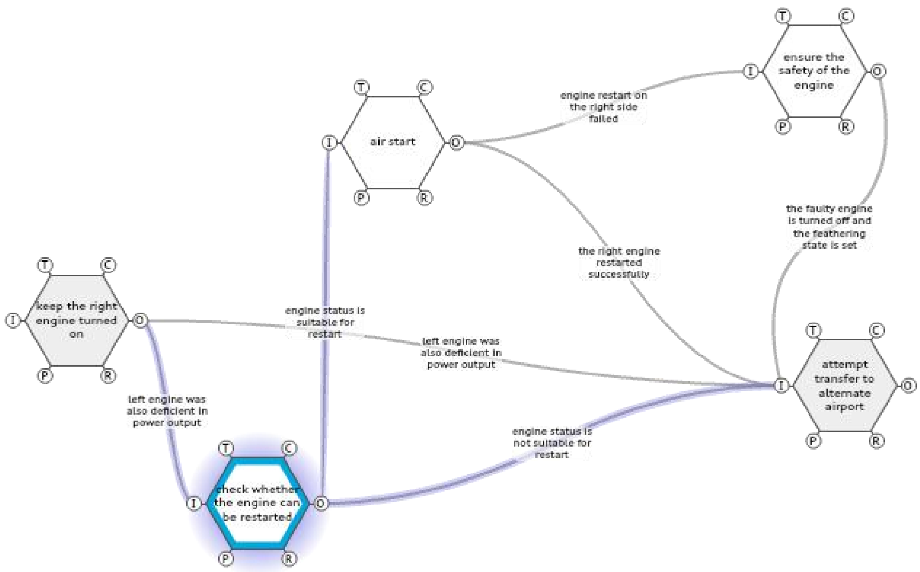

Fig 13. Possible practical example

The barrier analysed in the fourth step above can be achieved by appropriately changing the flight procedure. For example, add a note near the 'Engine Failure During Flight' chapter: In order to avoid an undesirable forced landing environment due to insufficient altitude of the aircraft, it is necessary to decide whether to restart the engine before losing the opportunity to restart, so as to provide more sufficient altitude for the aircraft.

2.3. Accident at Coventry Airport (United Kingdom)

After taking off from Coventry Airport, about 800 feet, the pilot selected the landing gear.

The landing gear transport lights were on, but the landing gear was not retracted. The pilot attempted to retract the landing gear many times, but the landing gear has not been retracted. As the landing gear was extended, the pilot observed that, in addition to the three landing gear down lights, the landing gear lights in the landing gear also turned on. The pilot reported the problem to ATC at Coventry Airport and his intention to return to land. The landing was uneventful.[17]

After collecting relevant information, the normal procedures related to this accident are Normal Take off, Approach and Landing. The relevant emergency procedure is Landing Gear Unsafe Warnings.[16]

2.3.1 Application of FRAM to Accident at Coventry Airport

A total of 7 essential functions are identified. The agents of these functions are mostly pilots, and the agent of 'ATC control' is the Air Traffic controller.

Table 3. List of functions of the FRAM model

Function	Agent
Take off	Pilot
Select the landing gear up	Pilot
Recycle the landing gear	Pilot
Land & Touchdown	Pilot
Apply the brakes	Pilot
ATC control	ATCO
Enter the climbing stage	Pilot

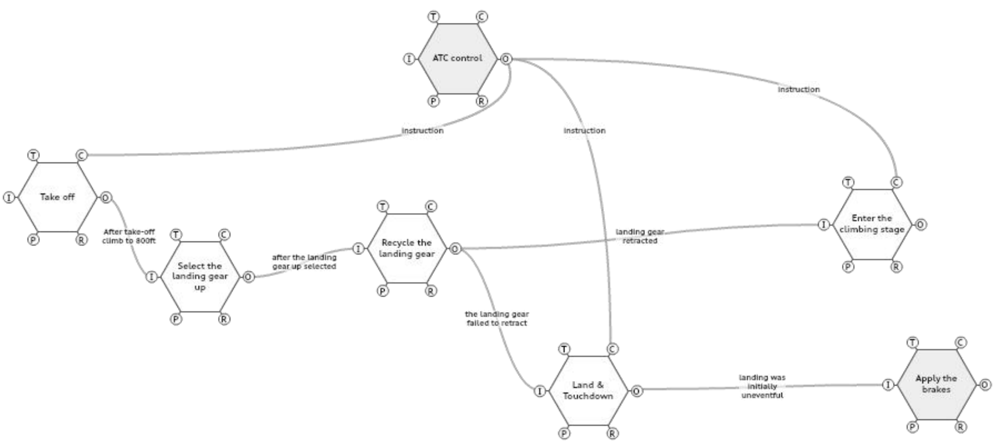

Fig 14. FRAM model of accident to Piper PA44-180 Seminole at Coventry Airport

In this analysis, variability exists in the availability of equipment. That is, whether the landing gear of the aircraft is normally retracted. The main factor of the accident was that the landing gear of the aircraft could not be retracted, which caused the aircraft to make a forced landing. After the plane took off, the pilot operated in accordance with the manual to retract the landing gear and encountered trouble in the process.

Satisfying the condition of resonance requires more than two variability and interaction. There is only one variability in this accident analysis, so there is no resonance. According to the records, all the pilot's movements belonged to the normal range. However, inspections by the aircraft maintenance agency revealed that the NLG lower lock pivot bolt was bent, causing the lower lock assembly to block the landing gear door and stop the retraction of the outriggers. The displacement of the lower lock mechanism prevents the nose leg from reaching the fully locked position but allows the micro switch for operating the downlight to be activated while the NLG is unlocked.

In the analysis of the accident through the FRAM model, the representation of each function and the couplings between the functions were determined with reference to the three flight procedures mentioned above. The results of the accident analysis point to the flight procedures that did not cause or amplify the occurrence of the accident.

2.4. Elne (France) accident

In the evening, a man turned over a barbed wire fence and entered Perpignan Rivesaltes Airport (Pyréneés-Orientales). After entering an aircraft that does not require a key to start the engine. He started two engines and then taxied to the taxiway where he took off. Under turbulent weather conditions, he flew at a low altitude near Perpignan for about an hour. During the turn, the aircraft entered a nose-down attitude and collided with the ground. The aircraft made a high-energy collision with the ground in the field.[18]

The normal procedures related to this accident are Taxiing, Take off, Cruising and Stall.[16]

2.4.1 Application of FRAM to Elne Accident

A total of 8 functions were identified. All functions will be performed by the pilot.

There are two variabilities in this accident analysis. The first variability is the function 'flight training'. Generally, after the flight training is completed, the pilot can control the aircraft relatively correctly. But the flight executor in this accident never received any training and did not follow the flight procedures. The flight executor cannot correctly respond to emergencies. This variability belongs to training, preparation, competence. The second variability is the output of function ‘turn the aircraft’, whether it remains in the controllable range when the flight executor turns the aircraft. If it exceeds the range, the aircraft will face a stall and cause the aircraft to crash.

Table 4. List of functions of the FRAM model

Function	Agent
Turn on the engines	Pilot
Taxiing	Pilot
Take off	Pilot
Cruising	Pilot
Return to the airport and turn the aircraft	Pilot
Stabilize the aircraft	Pilot
Return	Pilot
Flight training	Pilot

The first variability is the most critical, because the output of ‘flight training’ is a precondition for most of the functions in the schema. This variability and the second variability have a resonant effect and amplify the second variability. When the flight executor turned the plane, because he did not receive professional training, he did not control the turning range within the controllable range which caused the plane to stall and finally crashed.

The accident happened by chance because the plane was started and piloted illegally. The flight executor did not operate in accordance with the flight procedures. Due to the sudden nature of the accident, the direction of the accident cannot be predicted. According to the results of FRAM analysis, the main cause of the accident was that the flight executive had not received training. The loss of control of the aircraft caused by improper operation may occur at any stage of the event at any time. In order to dampen variability, it is necessary to ensure that each pilot has received adequate training and prevent any unauthorized entry into the airport.

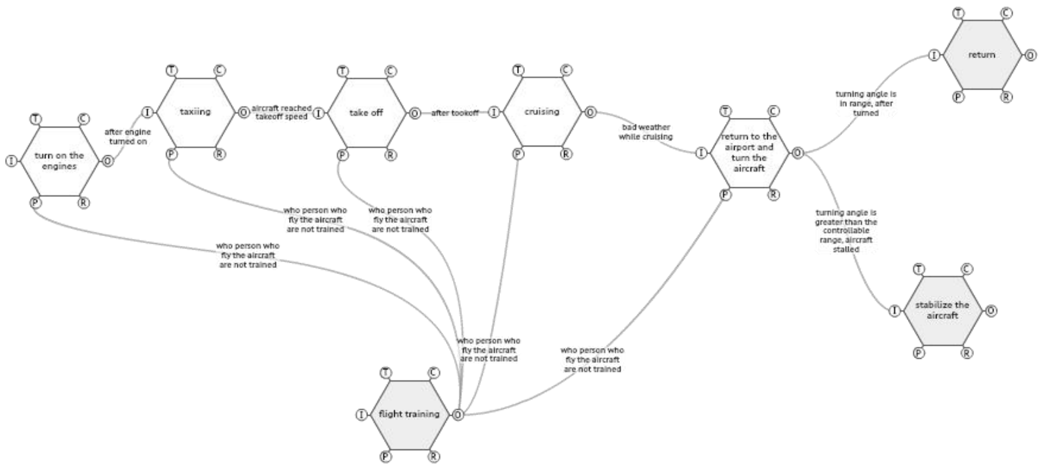

Fig 15. FRAM model of accident to the Piper PA44 Seminole registered F GCJE at Elne

During the entire accident, the flight executor did not follow the flight procedures. But through clues from surveillance and witnesses, relevant flight procedures can be inferred. Then, according to the relevant flight procedures, the accident analysis by FRAM model was completed. In addition, the importance of locking the aircraft after the end of the flight or maintenance needs to be reminded in the flight procedures.

2.5. EBST (Belgium) accident

This aircraft was used to familiarize two student pilots with different flight situations with one engine not working. According to the plan, the instructor started the L/H engine failure simulation after take-off. The student pilot stabilized the plane and flew on the airport circuit until the short final. At that moment, the student pilot claimed that he could not fully align the plane with the runway. The instructor took over control and landed the plane. As the aircraft rolled on the runway, the instructor reconfigured the aircraft's take-off control, and suddenly the aircraft turned to the left and toward the embankment perpendicular to the runway. The instructor decided to speed up the take off to regain control and avoid hitting the embankment. When a wing stalled and made several violent contacts with the ground, the aircraft just passed by the right side of the embankment. The instructor had been teaching flying for five hours when the accident happened.[19]

The normal procedures related to this accident are VMCA (Air Minimum Control Speed) Demonstration, One Engine Inoperative Landing and One Engine Inoperative Go-around. VMCA is the minimum flight speed at which a twin-engine aircraft can be directional controlled according to the Federal Aviation Regulations. The VMCA demonstration may require multiple engine ratings for FAA flight tests, approaching an uncontrolled flight condition, and the power of one engine is reduced. It needs to be carried out at an altitude of more than 4000 feet above the ground.[16] VMCA demonstration may be required for multi-engine pilot certification.

2.5.1 Application of FRAM to EBST accident

Step 1: A total of 12 functions were identified. All functions except 'see "MEP Training Handbook"' will be performed by the pilot. The MEP Training Handbook is the guidance of flight school procedure.

Table 5. List of functions of the FRAM model

Function	Agent
Take off	Student pilot
Demonstration of VMCA	Student pilot
Arrive back at EBST	Student pilot
Simulations of flight with one engine inoperative	Student pilot
Initiate a single-engine approach and landing simulation	Instructor pilot
Instructor pilot takes over control	Instructor pilot
Raise the flaps as preparation for take-off	Instructor pilot
Landing	Student pilot
Forced landing	Instructor pilot
Go around	Instructor pilot

Step 2: There are three variability in this accident analysis. The first variability is the output of the function 'see "MEP Training Handbook", because it is the resource for most of the functions in this schema. In training, both the instructor and the student should perform operations under the guidance of the flight manual. But because The MEP Training Handbook does not explicitly state that it is not allowed to simulate engine failure by closing the fuel selector valve. This causes this output to become a variability. The details will be described later. The second variability is the output of the function 'initiate a single-engine approach and landing simulation'. Under normal conditions, the aircraft will complete the landing. However, if the instructor is guided by the 'MEP Training Handbook', he does not realize that it is not allowed to simulate engine failure by closing the fuel selection valve. The

fuel selection valve will be closed. The third variability is the resource of the function 'instructor pilot takes over control'. That is, the instructor pilot, the work experience and fatigue of the instructor pilot affect his judgment and observation ability. Since the instructor pilot plays a leading role, this variability is also critical. In this accident, the instructor did not realize in time that the aircraft engine was really malfunctioning. He thought that the front wheel had a steering failure and chose to take off again.

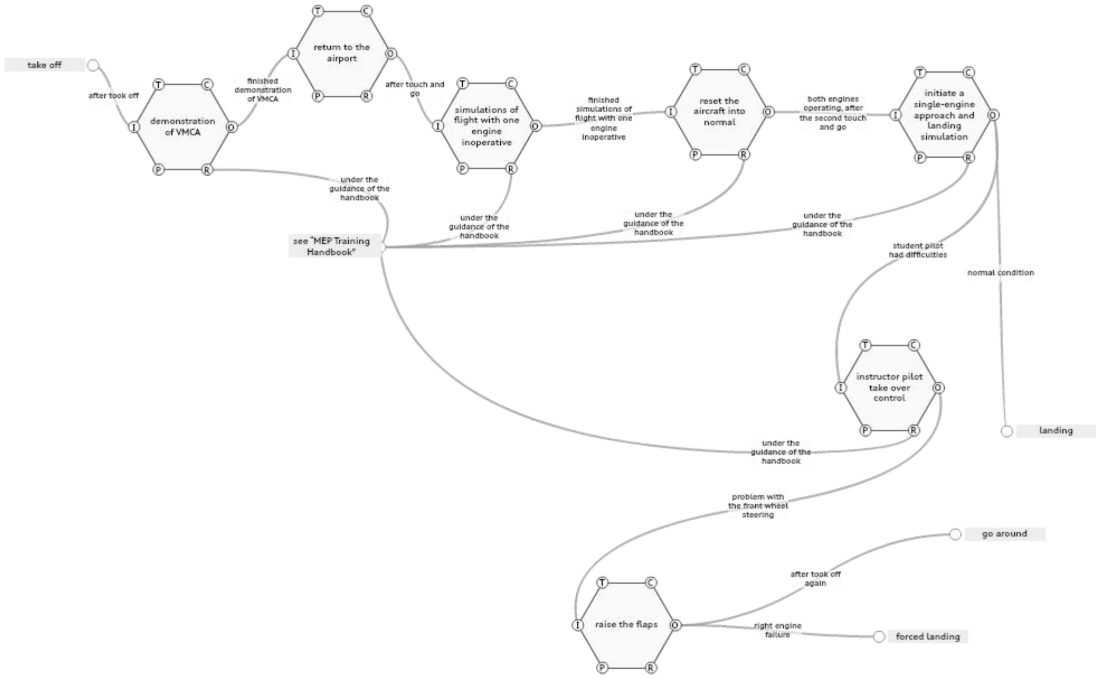

Fig 16. FRAM model of accident to Piper PA44-180 Seminole at Kinglake VIC

The first variability will not directly bring serious consequences, but it resonates with the other two variability and amplify the other two variability. Due to inaccurate statements, instructor pilots will be more inclined to make wrong choices. Table 5 shows an example of the aspects of the function ''Initiate a single-engine approach and landing simulation'' and 'Instructor pilot take over control'.

Combine the cause of the accident and FRAM analysis. The "MEP Training Manual" does not contain information related to the simulation of an engine failure. Due to the lack of information and guidance on how to evaluate and prevent the actual failure of the simulated engine in the MEP training manual, neither the pilot nor the observer is fully aware of the engine failure. The "VFR Training Manual" outlines the difference between real engine failures and simulated engine failures. In addition, this part of the manual also warns pilots of the danger of inducing actual engine failures during simulated engine failure exercises. A function parallel to the first variability can be added, linking all functions connected with the function ‘see "MEP Training Handbook"’. Thereby increasing the damping of the first variability. For example, add a function ‘see VFR Training Handbook’, and its output is connected to the resource of other functions in the schema.

Table 6. Two FRAM module function description

Function: Initiate a single-engine approach and landing simulation	Aspect description
Input	both engines operating, after the second touch and go
Output	student pilot had difficulties
Resource	under the guidance of the handbook
Function: Instructor pilot take over control	Aspect description
Input	student pilot had difficulties
Output	Problem with the front wheel steering
Resource	under the guidance of the handbook /instructor pilot

Apply the result obtained from the analysis in step 4 above to the flight procedure. It can also be specific, for example, to supplement the ‘MEP Training Handbook’. By adding the important information mentioned in the VFR, it is not only about the simulation of engine failure. In addition, both student pilots and instructors should be familiar with all flight documents.

2.6. Accident at Warton Aerodrome, Lancashire

The pilot executed an approach to runway 25. The surface was dry and the wind was light and from the north-west. After the occupant's feet left the rudder pedal, the main wheels of the aircraft touched down. Immediately afterwards, the front wheels descended sharply to the surface of the runway, and the aircraft began to diverge to the left. It was difficult for the pilot to bring the plane back to the centerline. It continued to pull vigorously to the left, and as the speed slowed down to a fast walk, it ran to the adjacent grass. Determining the final position of the aircraft will bring difficulties to the continued operation of the airport, so try to taxi the aircraft to a nearby taxiway C. During this operation, the right propeller hit the ground, damaging one of the blade tips.[20]

The normal procedures related to this accident are Approach and Landing.[16]

2.6.1 Application of FRAM to Accident at Warton Aerodrome, Lancashire

A total of 5 functions were identified. All functions except ‘tower control’ will be performed by the pilot. They are Approach, Landing, Taxiing to apron, Taxiing to a location that does not affect the operation of the airport. ‘Tower control’ will be performed by tower controller. There are two variabilities in this accident analysis. After the function "landing", the output "landed without no problem" and "out of control of front wheel steering" are connected to the functions ‘taxiing to apron’ and ‘taxiing to a location that does not affect the operation of the airport’ respectively. This variability is belonged to availability of equipment. Specifically, out of control of the front wheel steering is the first variability. The second variability is that after the function " taxiing to a location that does not affect the operation of the airport", the propeller eventually hit the ground. This means that the pilot cannot taxi to other positions as expected because he damaged the aircraft while doing so.

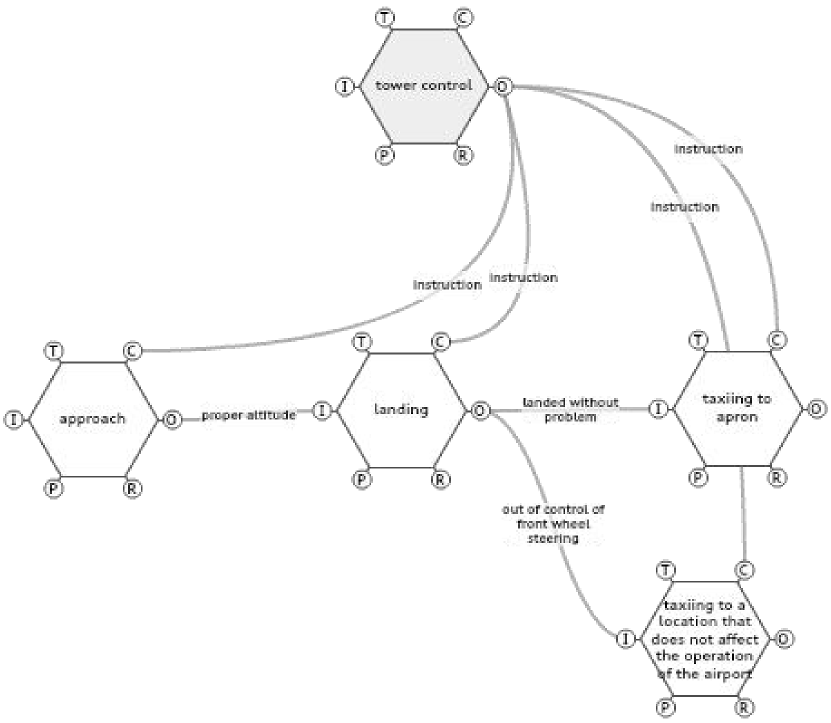

Fig 17. FRAM model of accident to Piper PA44-180 at Warton Aerodrome, Lancashire

These two variabilities have a resonance effect. After the front wheels of the aircraft are out of control, the aircraft cannot be transferred to the apron. However, in order not to affect the operation of the airport, the aircraft was damaged in the process of heading to the taxiway.

The first variability did not directly cause damage to the aircraft, but it amplified the second variability. In order to effectively control the second variability, the movement of the aircraft should be reduced when the front wheels are out of control. But I think a more effective way is to dampen the first variability. The loss of control of the front wheel steering is a technical reason. The simplest is to improve the stability of the front wheels.

3 Results

After the analysis of five accidents by FRAM model, three of the accident analysis results point to changes or additions to flight procedures. The table 7 is a summary of the analysis of the five accidents, including the relevant flight procedures and whether the flight procedures need to be changed or supplemented. Except for accident to Piper PA-44-180 Seminole at EBST, the flight procedure did not contribute to the accident.

Although the flight procedures did not contribute to the other two accidents, changes to the flight procedures can be used to prevent such incidents from recurring in the future. Regarding the accident to Piper PA-44-180 Seminole at EBST, there are many contributory factors of the accident. Cold and humid weather promoted the carburetor to freeze. The instructor pilot believed that the uncontrollable steering of the aircraft on the ground was due to the failure of the steering of the front wheels. The instructor may have been tired after flying for 5 hours. The missing information in the MEP training manual was a contributing factor, so the procedure was problematic. Because the MEP training manual shows the flight procedures used by instructor pilots and student pilots. In order to prevent the MEP training manual from becoming a contributory factor to accidents in the future, other parts of the content should also be checked for supplementation.

3.1. Relation of flight procedures with FRAM functions

Before linking the flight procedure to the FRAM function, we must first understand what a flight procedure is. There are five major procedures in general flight procedures. The figure 18 is a summary of flight procedures.

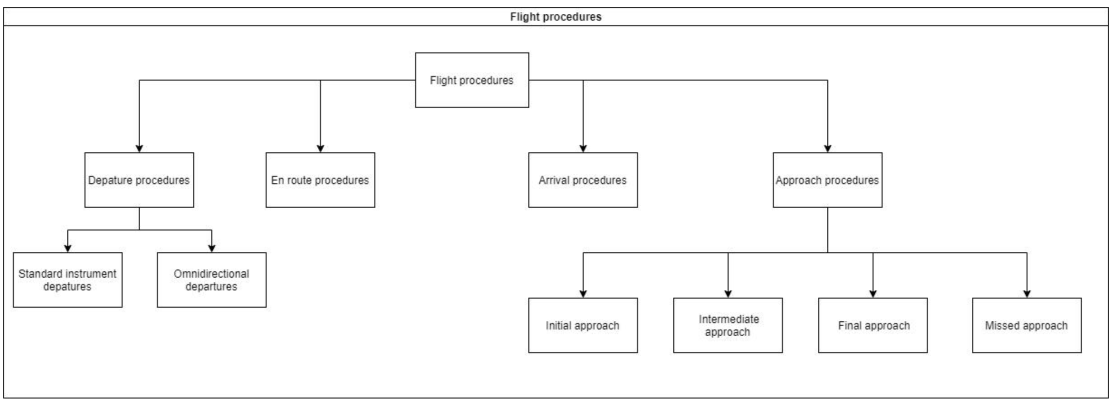

Fig 18. Summary of general flight procedures

Table 7. Summary of accidents analysis

Accident	Relevant flight procedures	Whether the flight procedures need to be modified or supplemented and proposal
Accident to Piper PA44-180 Seminole at Kinglake VIC	1. Engine Failure During Flight 2. Air Start	Yes Add a note near the chapter "Engine failure in flight": avoid an unfavorable forced landing environment caused by insufficient altitude of the aircraft, it is necessary to decide whether to restart the engine before losing the opportunity to restart, so as to provide more sufficient altitude for the aircraft.
Accident to Piper PA44-180 Seminole at Coventry Airport	1. Normal Take off Approach and Landing 2. Landing Gear Unsafe Warnings	No
Accident to Piper PA-44-180 Seminole Seminole at Elne	1. Taxiing 2. Take off 3. Cruising 4. Stall	Yes Add a reminder of the importance of locking the aircraft after the end of the flight or maintenance into the flight procedure.
Accident to Piper PA-44-180 Seminole at EBST	1. VMCA Demonstration 2. One Engine Inoperative Landing 3. One Engine Inoperative Go-around	Yes Supplement "MEP Training Manual" by adding important information mentioned in VFR.
Accident to Piper PA-44-180 Seminole at Warton Aerodrome, Lancashire	1. Approach 2. Landing	No

More detailed flight procedures can be the aerodrome flight plan of the departure aerodrome, arrival aerodrome and alternate aerodrome. They are represented by charts or text. There are also procedures in the relevant manuals of the aircraft. The flight procedures are series of maneuvering flights in sequence specified for the operation of the aircraft, including flight path, altitude and maneuvering area. Before performing FRAM analysis, the relevant flight procedures should be identified, and a whole flight procedure should be divided into independent activities or functions. For example, identify the flight procedures in the figure 18 as functions, adjust the seats, set the parking brake, turn off radios, turn on the alternators, etc. This is based on the principle of the FRAM model. The FRAM model provides a way to identify these elements and determine their interrelationship.

BEFORE STARTING ENGINES

Seats .... adjusted
Seat belts and harness .... fasten/adjust
check inertia reel
Parking brake .... set
Circuit breakers..in
Radios .... OFF
Cowl flaps ....OPEN
Carburetor heat.. OFF
Alternators... ON
Prop sync .... MANUAL

Fig 19. Normal procedures – before starting engines [16]

3.2. Link between FRAM functions and flight procedures

What I do is FRAM analysis of aircraft accidents related to flight procedures. First, analyze the flight procedures related to the target accident and find the relevant flight procedures documents. The required documents include aerodrome flight plan of the departure aerodrome, arrival aerodrome and alternate aerodrome and relevant manuals of the aircraft. By comparing accident history and flight procedures, each element that needs to be analyzed is determined. A special example is the above accident to the Piper PA44 Seminole at Elne (France). The accident history does not have a complete record of the intruder's behavior, but by comparing the witness and monitoring records with the flight procedures, its functions can be identified through clues: taxiing, take-off, cruise, etc.

It is worth noting here that events cannot be placed in hexagons. Function is an abstract concept. The FRAM model and its instantiation are different. The FRAM model shows all that can happen, instantiation refers to events that show how the functions were executed. Before starting the FRAM analysis, list all conceivable functions in the table and describe the functions in text. Then determine a function with a central role (e.g., a function that is more variable in specific accident). Start the analysis and start with this function firstly. Then connect all functions by describing the aspect description of each function. Due to the special nature of the FRAM model, it can be continuously made more complete. New functions can be added continuously because the FRAM model is not a flow type model.

3.3. Usefulness of linking FRAM functions with flight procedures

After completing a FRAM model, identify its variability. Identify the attributes of variability and provide effective evidence for accident analysis to judge the contributing factors of the accident. If there are multiple variabilities and their mutual influence will produce a resonance effect, our goal is to dampen the critical variability, which is to limit the possibility of bad things happening. Apply the results of the FRAM model analysis to reality, analyze the variability to determine whether there are possible factors that contribute to the current accident in the flight procedure. Then put forward effective changes or supplementary suggestions for the deficiencies in the flight procedures. These procedures can have a direct or indirect impact on the accident. In both cases, modification and supplementation of procedures can be used to dampen variability. When a new function needs to be added, the follow-up return to the flight procedure can be expressed as a new flight procedure or multiple flight procedures to be added, and the flight procedure can also be improved according to the specific situation.

4 Discussion

FRAM analysis of flight procedures has a certain value. The FRAM model exhibits the coupling that interacts within the system with a non-linear effect. The FRAM model effectively depicts the variability of performance and helps analysts understand it. Its advantage is that it can be used to analyze a complex system, aviation is a complex system. There are many different levels of interaction in the aviation system, which is difficult to interpret with a linear model. For example, when a pilot performs a series of operations, he needs to be under the control or guidance of the ATC controller. FRAM model can realize the coupling of these different levels of functions through six aspects (O, output; I, input; C, control; P, precondition; R, resource; T, time). Linking flight procedures to FRAM analysis provides a broader perspective and generalizes the elements, the application of the results of accident analysis can be extended to a wider range, rather than just a single independent event. Then make the results more convenient to use in similar events. And in the process of accident analysis, a generalized concept can effectively help the analyst understand the specific situation relative to the flight procedure to find and dampen the variability existing in the flight procedure.

But relatively, it takes more time. Because the analysis using FRAM model is a qualitative method, it would take a lot of time to study the event itself and the FRAM model. Coupled with the association with flight procedures, it is also necessary to compare and identify related flight procedures. This increased workload requires more time.

From my analysis of five accidents, not every accident is related to its flight procedures. Because the flight procedures have been strictly reviewed before being published, the published flight procedures may not contain major errors. Accidents caused or contributed to by flight procedures are rare. Among five accidents I mentioned, only one accident to Piper PA-44-180 Seminole at EBST contributed by one of the flight procedures. But after the accident analysis is completed, the results can be linked to flight procedures. Link damping variability to flight procedures. Out of the five accidents, three of the accident analysis results point to solutions that are linked to flight procedures. Because changes or supplements to flight procedures are effective ways to avoid related problems from happening again. In the accident analysis of Piper PA44-180 Seminole at Kinglake VIC, I mentioned that adding the function ‘check whether the engine can be restarted’ in the FRAM model to follow up to the flight procedure can be adding a reminder.

Associating the accident history with the flight procedure at the beginning of the accident analysis makes it easier to find the variability that may exist in the flight procedure or to more accurately locate the damping required by the variability in a specific procedure.

I think the FRAM model also has some shortcomings. When constructing the FRAM model, the functions to be analyzed are set and described according to the FRAM principle. Although the work is basically relatively simple, the higher the complexity of the analyzed system, the greater the workload. With manual input, it takes a lot of time to complete. After the model is completed, the identification of variability can be qualitatively based on the attribute types in CPCs, but there is a lack of reference structural suggestions for the barriers of variability damping. For example, this can be achieved through the analysis of many FRAM analysis parts of the barrier setting. Analyze the possible commonalities among them, classify and define the common barriers as a more general conceptual barrier. If a suggestive framework is established, it can help analysts to make the results of the accident analysis more relevant to the FRAM model when performing the fourth step in the FRAM analysis. Instead of just serving the accident itself.

5 Conclusion

In the whole work, I first gave a brief overview of flight procedures from five categories. Then there is an introduction to the FRAM model, including its working principle and my understanding of it after studying. After collecting literature, I found 11 articles that applied the FRAM model to aviation accident analysis. I analyzed their work and looked for helpful experiences. And cited two interesting examples to conduct a deep analysis of their work. Then I started a case study, searched five accidents/incidents and their investigation information, and then identified the flight procedures related to them. Then FRAM analysis is performed on each accident/incident according to four steps, and the FRAM functions are linked to the flight procedure. After completing the analysis, some suggestions were made to reduce the risk. And then I followed up the FRAM analysis back to the flight procedure, where feasible.

One of the limitations of this paper is that before starting work I expect at least one accident which is caused by flight procedures. So, there can be a more typical example to illustrate the relevance between flight procedures and FRAM analysis. The contributing factors of the accident are varied. This article only analyzes 5 cases, which may not be comprehensive. Since not all details could be identified from the accident, the variability and resonance analysis in the accident analysis is more general, without all possible details. In addition, this article does not verify the results of the accident analysis in reality, but only check the model theoretically.

In future work, it may be possible to use both the FRAM model and other linear process models for accident analysis. Because the linear process model can show the entire accident process, the FRAM model is designed to analyze the variability and resonance effects. Combining the two can make up for each other's shortcomings and make the accident analysis more comprehensive. In addition, because it takes a lot of time to analyze the results when using the FRAM model, the available software should be upgraded.

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