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FRAM Analysis of Aircraft Landing Phase with Focus on Runway Excursion

Christianne Reiser[1], Emilia Villani[2], Moacyr Cardoso Junior[2]
[1]Embraer S/A, São José dos Campos/SP – Brasil
[2] Instituto Tecnológico de Aeronáutica (ITA), São José dos Campos/SP – Brasil

Abstract – Runway excursion is the type of aircraft accident that most frequently occurs, contributing to around 25% of the occurrences. To reduce this rate, several countermeasures have been proposed in the last years; mainly based on aircraft incident investigation and analysis. In order to search for further Aviation System improvements to avoid runway excursions despite of these occurrences, an application of the FRAM (Functional Resonance Analysis Method) focusing on the landing phase is proposed. This method proposes the exploration of how functional variability can escalate into unexpected, and often unwanted, events. It has been used for accident analyses and risk assessments in safety.

Keywords – Flight Safety, FRAM, Runway Overrun.

I. INTRODUCTION

Nowadays the progress in safety management made flying one of the safest ways to travel, reaching a rate of 1.25 commercial jets accidents per 1 million flights [2]. Even though the number of accidents per flight has been decreasing with time, the number of fatalities per year has been variable, without dropping due to the growing number of aircraft in operation and their increasing capacity (Fig. 1).

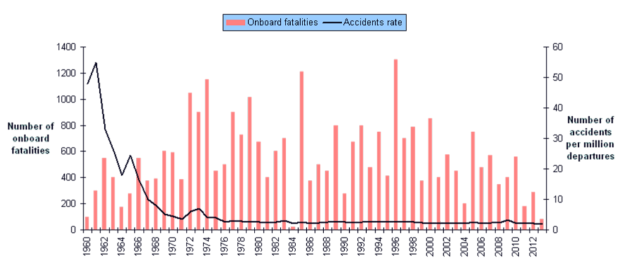

Fig. 1. Evolution of the Number of Accidents and Fatalities (Source: 1001crash.com)

The aircraft accidents rate reduction was substantial only until the 80s in the so-called age of technology, in which safety concerns focused on guarding machinery, stopping explosions and preventing structures from collapsing. The focus on technology as the main – or even only – source of both problems and solutions in safety was successfully maintained until 1979, when the accident at the Three Mile Island (TMI) nuclear power plant demonstrated that safeguarding technology was not enough. The TMI accident brought to the fore the role of human factors and made it necessary to consider human failure as a potential risk. Seven years later the loss of the space shuttle Challenger, reinforced by the accident in Chernobyl, required yet another extension, this time by adding the influence of organizational failures and safety culture to the common lore [5].

ICAO defines safety as "the state in which harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and risk management" [1]. This traditional definition of safety as "a condition where nothing goes wrong or where the number of things that go wrong is acceptably small" is called Safety-I. The purpose of managing Safety-I is consequently to achieve and maintain that state [5], such as 1 accident per 1 million flights.

Safety-I management focus on aviation is to analyze the events from latent circumstances to the flight crew errors, monitoring the potentially unsafe conditions in the day by day operation as well as the reportable occurrences. Latent circumstances are often related to deficiencies in organizational processes and procedures. Flight crew errors may be a result of an ineffective management due to, for example, deficient trainings, unspecific policies, or even airline pressures. In other words, the so-called Safety-I approach promotes a bimodal or binary view of work and activities, considering acceptable and unacceptable outcomes as two distinct and different modes of functioning: things go right because the system functions as it should and because people work as imagined, things go wrong because something failed (Fig. 2). It is then possible to achieve safety only minimizing, or even blocking, the transition from normal to abnormal functioning [5].

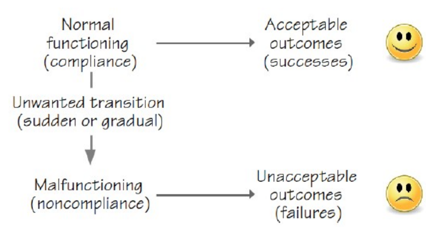

Fig. 2. Safety-I Basis [5]

Although this conception paved the way to outstanding improvements in safety research, they seem to be not so effective for socio-technical systems: that are incompletely understood, whose descriptions can be complicated, and that changes are frequent and irregular rather than infrequent and regular [7]. Safety-II aims to fill this gap, assuming that everything basically happens in the same way, regardless of the outcome (Fig. 3). This concept accepts that individuals and organizations habitually adjust their performance to match current demands, resources and constraints in order to compensate the incompleteness of procedures and instructions. Following Safety-II, the definition of safety shifts to consider not only the adverse outcomes, but also positive and negative events, in order to achieve a holistic view of the system and in-depth understand its functioning.

Safety-I aims to limit performance variability, Safety-II requires to manage it proactively, rather than simply constrained it [5].

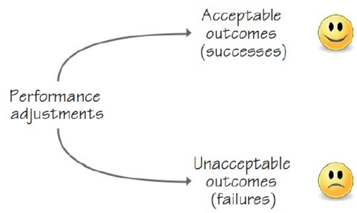

Fig. 3. Safety-II Basis [5]

The Functional Resonance Analysis Method or FRAM [4] provides a way to describe outcomes using the idea of resonance arising from the variability of everyday performance [8]. The purpose of this work is to apply the traditional FRAM for an event investigation related with an aircraft approach/landing procedure - the runway overrun.

II. Method

The FRAM is a method-sine-model, whose purpose is to build a model of how things happen rather than to interpret what happens in the terms of a model. The four principles on which it is built are:

- That failures and successes are equivalent in the sense that they have the same origin. Another way of saying that is that things go right and go wrong for the same reasons.
- That the everyday performance of socio-technical systems, including humans individually and collectively, always is adjusted to match the conditions.
- That many of the outcomes we notice – as well as many that we do not – must be described as emergent rather than resultant.
- Finally, that the relations and dependencies among the functions of a system must be described as they develop in a specific situation rather than as predetermined cause–effect links. This is done by using functional resonance [4].

The FRAM does not imply that events happen in a specific way, or that any predefined components, entities, or relations must be part of the description. Instead it focuses on describing what happens in terms of the functions involved. These are derived from what is necessary to achieve an aim or perform an activity, hence from a description of work-as-done rather than work-as-imagined. But functions are not defined a priori nor necessarily ordered in a predefined way such as hierarchy. Instead they are described individually, and the relations between them are defined by empirically established functional dependencies [4].

Based on [4] and [7], the following paragraphs present the four steps to perform a FRAM analysis. However, in the so-called Step 0, it is necessary to make clear whether the analysis is an accident investigation or a risk assessment.

A. Step 1: Functions Identification and Description

The first step of the FRAM is to identify the functions that are needed for everyday work to succeed. Six different aspects can characterize each function as follows. They are traditionally at the corners of a hexagon, which represent the function itself (Fig. 4).

- **Input (I):** what starts the function or what is processed or transformed by the function.
- **Output (O):** the result of the function, it can be either an entity or a state change and serves as input to the downstream functions.
- **Precondition (P):** mandatory conditions that must exist before carrying out the function. Preconditions do not necessarily imply the function execution.
- **Resource (R):** what the function needs when it is carried out or consumes to produce the output.
- **Control (C):** what controls and monitors the function, regulating its performance to match the desired Output.
- **Time (T):** temporal requirements or constraints of the function, regarding both duration and time of execution.

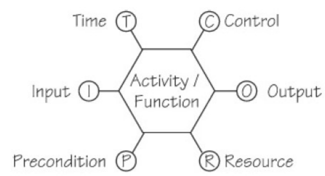

Fig. 4. A Hexagon Representing a Function [4]

It is possible to divide functions into two classes: foreground and background. The foreground functions represent the core of the analysis, requiring a complete definition of all the six aspects, when possible. The background functions represent the components not in scope of analysis and therefore they need only one input or one output.

B. Step 2: Performance Variability Characterization

The purpose of the second step is to characterize the variability of the functions that constitute the FRAM model. One way to do that is to distinguish among different types of functions, for instance technological, human and organizational.

- **Technological** functions are carried out by various types of 'machinery'. Since they are designed to be highly predictable and reliable, the default assumption of the FRAM is that they do not vary significantly during the scenario that is analyzed.
- **Human** functions are carried out by humans, either as individuals or in small groups. In a FRAM analysis it is important to recognize that the frequency of human performance variability is high, and that the amplitude is large. The high frequency means that performance can change rapidly, sometimes even from moment to moment. The large amplitude means that differences in performance can be large, sometimes dramatically so – for better or for worse. The variations in both frequency and amplitude depend on many different things, including working conditions.
- **Organizational** functions are carried out by groups of people, where the activities are explicitly organized. For a FRAM analysis, the frequency of organizational performance variability typically is

low but that the amplitude is large. Organizational performance changes are slow, exemplified by alterations to rules, regulations or policies. But the differences in performance, that is, the amplitude, can be large.

Having considered some of the possible sources of variability, the next question is how performance variability will show itself – either in the sense of how it can be observed or detected – or in the sense of how it may affect downstream functions. A simple solution to describe the consequences of performance variability is to note that the Output from a function can vary in terms of timing and precision.

- In terms of **timing**, an Output can occur too early, on time, too late or not at all.
- In terms of **precision**, an Output can be precise, acceptable or imprecise. Since it refers to the coupling between upstream and downstream functions, the precision is relative rather than absolute. If the Output is precise, it satisfies the needs of the downstream function. An acceptable Output can be used by the downstream function but requiring some adjustment. An imprecise Output is something that is incomplete, inaccurate, ambiguous or in other ways misleading.

C. Step 3: Variability Aggregation

The FRAM represents the potential couplings among functions, not showing the effects of a specific scenario. This step focuses instead on examining specific instantiations of the model to understand how the potential variability of each function can become resonant, leading to unexpected results, as stated by the functional resonance process. It is therefore necessary to identify the functional upstream-downstream couplings. The variability of a function results as a combination of the function variability itself and the variability deriving from the outputs of the upstream functions, depending on the function type and the linked aspects type. This paper deals qualitatively with this step, based on potential for dampening performance variability ranges from +1 to +3 and for increasing performance variability ranges from -1 to -3 [6].

D. Step 4: Variability Management

This last step consists of monitoring and managing the performance variability, identified by the functional resonance in the previous steps. Performance variability can lead both to positive and negative outcomes. The most fruitful strategy consists of amplifying the positive effects, i.e. facilitating their happening without losing control of the activities, and damping the negative effects, eliminating and preventing their happening.

III. CASE STUDY

Runway excursion is a veer off or overrun off the runway surface. It occurs when an aircraft departs the runway in use during the take-off or landing run [9] and characterize at around 25% of the worldwide accidents [2]. This work contemplates the landing phase, once an aircraft is unable to stop before the end of the designated runway.

The runway overrun during landing precursors have been identified as adverse weather, deficiencies in airport facilities, wet or contaminated runway surface and flight crew operational deviations such as:

- **Unstable approaches:** an approach during which an aircraft does not maintain at least one of the following variables stable - speed, descent rate, vertical/lateral flight path and in landing configuration, or receive a landing clearance by a certain altitude.
- **Long touchdowns:** occurs when an aircraft touches the ground too far away of the aiming point, which is circa of 1,000 feet.
- **Inadequate or late use of deceleration devices**, such as ground spoilers, engine thrust reverser, normal or even emergency brakes.
- **Non-adherence to SOP** (Standard Operating Procedures) **and callouts.**

Based on these precursors, the current FRAM analysis starts at the clearance for approach and ends with an aircraft in taxi speed - around 30 knots. For a typical flight some of the following functions may be included:

- **To Provide Clearance:** a background and human function that initiates the current analysis as soon as the Air Traffic Controller (ATC) clears the aircraft for landing.
- **To Provide Information:** a background and human function that provides the meteorological and the terminal conditions (METAR/ATIS) through the ATC as a resource for "To Perform Approach Briefing".
- **To Perform Approach Briefing:** a foreground and human function that may be performed after the ATC clearance for landing, whose output is the alignment between the flight crew regarding the landing procedure. It consists of a precondition for "To Start the Approach" and uses some information from the ATC, such as the METAR/ATIS.
- **To Start Approach:** the flight crew starts the approach after the ATC Clearance. This foreground and human function shall follow the approach briefing and uses aerodrome approach charts.
- **To Provide Landing Procedure:** a background and technological function that makes approach charts available as a resource for "To Start Approach" and Instrument Landing Systems (ILS) as a resource for "To Capture Glideslope".
- **To Adjust the Flight Path:** a foreground and human function responsible for maintaining the flight path as well as a steady descent rate during the approach until the aircraft reaches 50 feet. Glideslope is used as a resource.
- **To Capture Glideslope:** a foreground and human function that shall follow the aircraft configuration and uses the ILS as resource. It begins during the approach procedure and supports the flight path adjustment.
- **To Configure Aircraft for Landing:** the flight crew shall configure the aircraft for landing, such as landing gear extension and the slat/flap positioning, as soon as they start the approach in accordance with the Operational Procedures and based on aircraft conditions due to the possibility of some systems

faults. This foreground and human function acts as a pre-condition for “To Capture Glideslope”.

- **To Set the Autobrake:** the flight crew chooses the autobrake mode based on Operational Procedures and in the runway characteristics as well as its surface condition. It is a foreground and human function that could be part of “To Configure Aircraft for Landing”. However, it is treated separately due to its importance for the aircraft deceleration. This function may be interrupted by the flight crew through brake pedal inputs and is not available when the normal brakes are at fault.
- **To Provide Runway Information:** a background and organizational function that provides the runway characteristics, like markings for the “To Touchdown” and length for “To Set Autobrake” and “To Press Brake Pedal”.
- **To Set Speeds:** a foreground and human function responsible for maintaining the speed stable during the approach until the aircraft reaches 50 feet. Operational Procedures are used as a reference.
- **To Recommend Procedures:** the airline adapts the Standard Operational Procedures (SOP) into their reality, generating the Operational Procedures as a control for some functions performed by the flight crew. It is a background and organizational function.
- **To Make Available the Operational Procedure:** manufacturer provides information regarding aircraft design and performance, including the SOP. It is a background and organizational function.
- **To Touchdown:** the flight crew performs a flare and touches the aircraft on ground in this foreground and human function, using the runway markings as reference. Flare is the descent rate reduction in order to perform a smooth landing. It occurs near to the ground (less than 50 feet Above Ground Level (AGL)). Its output starts the functions that decelerate the aircraft.
- **To Open Ground Spoiler:** as soon as the aircraft is on ground, the ground spoiler is opened in order to increase the runway surface friction. This action occurs automatically in the aircraft under analysis and is then considered a foreground and technological function.
- **To Apply Thrust Reverser:** the flight crew opens the engine thrust reverser when the aircraft is on ground, if available. It is a foreground and human function that benefits the aircraft deceleration.
- **To Press the Brake Pedal:** the flight crew presses the brake pedal in order to decelerate the aircraft. This foreground and human function disable the autobrake, if necessary, and decelerates the aircraft directly or through the anti-skid function. The available runway length may interfere its execution.
- **To Apply Brake Pressure:** a foreground and technological function, whose output is based on the autobrake selection or brake pedals application as input. The runway surface conditions influence the output when the anti-skid system is ON.
- **To Apply Emergency Brake:** a foreground and human function that should be active only when the normal brakes are at fault. It is controlled by “To Recommend Procedures”.
- **To Decelerate the Aircraft:** aircraft reduces its groundspeed until the taxi speed as soon as the aircraft touches the ground. “To Open Ground Spoiler” and “To Apply Thrust Reverser” are conditions that increment the deceleration capability. The performance of the aircraft depends on parameters from “To Provide Aircraft Status” like gross weight, pressure altitude, wind, flap position, engine and wing anti-icing systems status. This function is controlled by the “To Apply Brake Pressure”, “To Apply Emergency Brake” and “To Provide Adequate Runway Surface”. “To Provide Aircraft Status” also anticipate the Groundspeed that is being consumed.
- **To Provide Adequate Runway Surface:** airport infra-structure shall provide an adequate runway surface friction as well as a predictable variation due to weather conditions. Its output influences directly the capability of the aircraft’s deceleration. It is a background and technological function.
- **To Provide Aircraft Status:** a background and technological function that describes all the information available and used by the flight crew during landing.
- **To Taxi:** a background and human function that ends the current analysis.

Fig. 5 shows a diagram with the already described functions as well as a painted marking, such as green for the technological functions, red for the human ones and blue for the organizational. These functions were all considered relevant to explain the performance variability of the “To Decelerate the Aircraft”, whose output is the focus of the current analysis.

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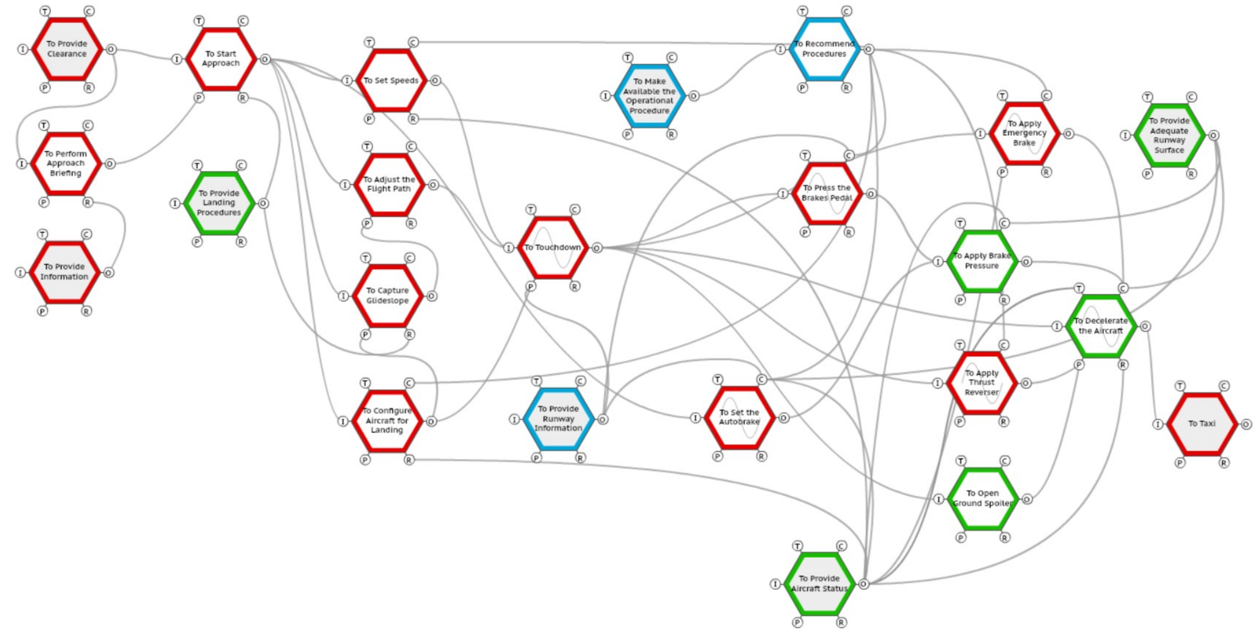

Fig. 5. FRAM Diagram for Aircraft Approach and Landing

For the purpose of illustration, it is reasonable to focus on the "To Decelerate the Aircraft" function to understand a little about the system variability. This is the most important function for this study and is affected directly by other 7 functions as shown in Table 1.

TABLE 1. INFLUENCE IN "TO DECELERATE THE AIRCRAFT"

Function	Timing	Precision	Influence
To Touchdown	Too late	Precise	3
To Apply Thrust Reverser	Too late	Precise	-2
To Open Ground Spoiler	On time	Precise	0
To Provide Aircraft Status	On time	Precise	0
To Apply Brakes Pressure	On time	Imprecise	1
To Apply Emergency Brake	Too early	Imprecise	1
To Provide Adequate Runway Surface	On time	Imprecise	2

Most of the upstream functions have a positive influence as their variability usually reduces the aircraft deceleration capability. The function "To Apply Thrust Reverser" has a negative influence because it is related with an optional system that increases the deceleration capability when used, regardless of its variability.

Ground spoilers dump the lift generated by the wing and maximize the wheel brake efficiency, being crucial for the deceleration. However, the function "To Open Ground Spoiler" is automatically performed by the aircraft under analysis and, initially, it has no variability. This assumption is also used for "To Provide Aircraft Status".

Despite of being a technological function that normally occurs on time with an acceptable precision, the variability deriving from the outputs of the upstream functions reaches a range of 1 as a result of the influences' median. The aggregation by itself indicates that the investigation continues in order to identify how performance variability can be observed and dampened in the upstream functions. For example, the variability of the "To Touchdown" function is derived from other functions, "To Set Speeds", "To Adjust the Flight Path", "To Configure Aircraft for Landing" and "To Provide Runway Information".

IV. CONCLUSION

FRAM is a paradigm shift since it can describe an overall activity without fixing the sequence of events. The diagram illustrates how the method builds up an explanation of the everyday work. It is not necessary to begin with a complete list and the analysis may identify further functions to be included. Since the functions are not ordered, e.g., in a sequence or a hierarchy, they can easily be added or removed at any time [3].

The relationship among the functions based only in the output variability is an insight and also the challenge. The performance of any specific part of a system, a function carried out by the flight crew, by the aircraft, or by the airline, may have a subliminal variability during the landings, hence not noticeable. Eventually, the combined performance variability of all the functions becomes detectable due to an overrun, for instance. Here, the functions variabilities were identified qualitatively and based on overruns historical data. This approach is too subjective and further approaches are being evaluated.

To manage performance and to control the sources of performance variability is possible only if their influence is well-known, and based on the work-as-done.

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