FRAM: A complex system's approach for the evaluation of aircraft on-ground deicing operations

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Abstract: Proper aircraft on-ground deicing operations are critical for the safety of aviation. The complex work environment of deicing operations requires continuous performance adjustments to cope with the dynamic work conditions. This study aims at presenting a new approach by examining the applicability of the Functional Resonance Analysis Method (FRAM) to evaluate performance in aircraft on-ground deicing operations and related issues that might endanger flight safety. To achieve this purpose, the deicing socio-technical system was modeled to analyze the SAS flight 751 crash at Gottröra in 1991 and show how safety issues can arise through the combination and overlapping of functional variability. The results demonstrate the usefulness of FRAM as an additional tool that can be applied in a complementary way with the existing methods.

Keywords: risk, safety, deicing, assessment, aviation, functional resonance analysis

1. Introduction

The "Clean Aircraft Concept" requires the removal of any ice, frost or snow contaminants from the aircraft surfaces prior to takeoff (Transport Canada 2004). The execution of aircraft deicing operations occurs in a complex working environment under very dynamic conditions. The sociotechnical system of deicing operations is characterized, among other factors, by tight time schedules, extreme weather conditions, work overload and stress, etc. (Transport Canada 2004). Such factors affect the capabilities of deicing workers and might degrade their performance. Accordingly, performance adjustments are continuously necessary to provide adequate operations as required by procedures and regulations. Despite the significance of deicing operations to aviation safety, research has rarely been conducted to analyze performance-degrading factors from a human factors perspective. Traditional safety assessment methods and investigation tools focus primarily on identifying errors, singular events or failures of systemic components (Leveson 2011). Classical approaches are not sufficient to provide a complete and comprehensive analysis of modern sociotechnical systems (Leveson 2011). Many issues in the applications of aircraft deicing procedures arise due to the complexity of the deicing operations and the context, in which they are performed. The main objective of this study is to examine the applicability of a new approach, namely the Functional Resonance Analysis Method (FRAM) (Hollnagel 2012), to evaluate performance in deicing operations and possibly resulting safety issues. Therefore, the context of deicing operations was modeled to analyze a case study, which should demonstrate the applicability and advantages of FRAM. As a scenario for analysis, the crash of the SAS flight 751 at Gottröra, Sweden, in 1991 was selected. The interesting aspect about this accident is that it happened despite the efforts of the flight crew and deicing technicians to clean the aircraft. It presents a suitable case to demonstrate how accidents can result from routine performance adjustments and the combination of variability in the execution of required tasks. The FRAM analysis considering the contextual conditions shall explain the gradual development of the accident through the overlapping of functional variability within the deicing sociotechnical system. The analysis thus will provide a new perspective to understand how accidents come to happen rather than simply providing a list or sequence of mistakes and failures as causes.

2. Scandinavian Airlines Flight 751

On December 27, 1991, an aircraft of Scandinavian Airlines (SAS) of type DC-9-81 took off at 08:47 hrs. at Stockholm/Arlanda and crashed four minutes and seven seconds later in a field in Gottröra. The aircraft had arrived the night before at 22:09 hrs. coming from Zurich and was scheduled to fly to Copenhagen in the morning. It cruised for approximately one hour and forty minutes at altitudes with outside temperatures between -53°C and -62°C and landed with 2550 kg of cold fuel remaining in each wing tank, which represents 60% of the tank's capacity. The aircraft was parked outdoors at gate 2 at the international terminal during the night. The weather conditions during the night and in the morning before takeoff were ideal for clear ice formation (Temperature between -0°C and +1°C) (SHK 1993).

A flight technician inspected the aircraft during the night and noted that clear ice has formed on the wings. In the morning, the mechanic noted the formation of frost on the wings' undersides. The formation of rime on the lower surfaces was a clear indicator that clear ice might have formed on the upper surfaces. The mechanic climbed the ladder, put his knee on the wings' leading edge and checked the upper side of the left wing near the fuselage. The mechanic concluded wrongly that there was no clear ice formation. The Pilot In Command (PIC) was fully responsible for ensuring that deicing has been performed adequately and that the "Clean Aircraft Concept" was maintained. The technical division was responsible for the deicing application and inspecting that it was done adequately. The technical division issued during the year bulletins and provided training to prepare personnel for the winter season. Each mechanic was provided with a checklist, which required that a tactile inspection must be performed to check the wings' upper surfaces for clear ice. The provided instructions did not specify how the inspection was to be performed exactly, how to remove clear ice and how to report to the PIC. The means provided to the mechanic did not allow him to reach the area, where the clear ice really formed. The mechanic should have climbed onto the wing completely to check all spots carefully and thoroughly. The wing's slippery condition did not allow such a practice to take place. The mechanic consulted with the PIC and requested deicing for both upper and lower sides of the wings. The aircraft was filled with additional 1400 kg of fuel and was ready at 08:30 hrs. for deicing. A total of 850 liter of heated deicing fluid type I at 85°C was applied for deicing. The upper wings' sides were deiced again after a first spraying to ensure a full removal of slush and snow. The mechanic did not check again after deicing for clear ice, since he assumed there was no clear ice present and the instructions did not require doing so. The deicing technician operating the spray nozzle reported that "*he saw that one of the four indication tufts fixed on the upper side of each wing moved during spraying*" (SHK 1993). A passenger sitting at the window during the deicing operation contradicted that story and reported that the tufts did not move. The mechanic informed the PIC that deicing was finished and the aircraft was clean and "*perfect*". The aircraft was taxied afterwards to runway 08 for takeoff (SHK 1993).

The risk of clear ice formation and ingestion by the engines was common to this aircraft type due to the aircraft design and configuration of the wing tanks. This issue was known to SAS and it was covered in internal information and bulletins. However, the training of the MD-80 pilots did not deal with the issue of clear ice and there were no special instructions for the pilots on how to act in case of clear ice risk. The technical staff was familiar with the issue of clear ice through training and the Line Maintenance Handbook (LMH) required inspecting the wings' upper surfaces tactually in case of doubt of clear ice formation. However, the LMH lacked detailed instructions on how to perform the clear ice inspection and report observations of clear ice. The technical staff lacked as well special tools and means to reach the clear ice area on the upper side of the wing without endangering their personal safety (SHK 1993).

3. Methodology

The Functional Resonance Analysis Method (FRAM) will be applied to analyze the deicing operation and departure procedure for flight SK751. The distinction about FRAM is its ability to describe adverse outcomes as a result of the combinations of functional variability (Hollnagel 2012). FRAM relies on four principles: equivalence of success and failure, approximate adjustments, emergence of failures and functional resonance (Hollnagel 2012). The first step is to identify and characterize the functions to construct a FRAM model for the deicing operation and takeoff process of SK751. FRAM functions are characterized by six aspects: Input (I), Output (O), Preconditions (P), Resources (R), Time (T), and Control (C) (Hollnagel 2012). Each function is described in the form of a table listing all its characteristics. The data to construct the model was obtained mainly from the official accident report published by the Board of Accident Investigation (SHK) in 1993. The analysis will be limited to the deicing and departure procedures until takeoff. Past takeoff, events are beyond the scope of this study. There are three types of functions: organizational, technological and human functions. Secondly, the sources of variability within the constructed model are to be determined and characterized. Variability is characterized in terms of timing (early, on time, too late and omission) and precision (imprecise, acceptable and precise) (Hollnagel 2012). Finally, the third step is to determine how that variability combined and resonated to eventually lead to the crash (For further information on FRAM, please consult the website: *http://www.functionalresonance.com*).

4. Results

The governmental agency STK did not follow up on their supervision duties after assigning a new technical representative at Arlanda and "*assumed*" that the clear ice problem "*was being well taken care of through SAS' own checks*" (SHK 1993). The control aspect provided by the function "Regulations & Supervision" was "imprecise" and influenced the performance of the SAS functions "Provide Instructions & Guidelines", "Provide Training" and "Provide Resources & Equipment". The instructions and guidelines provided by SAS were found "*inadequate to ensure that clear ice was removed*" (SHK 1993).

Table 1: *The list of the FRAM functions with respective outputs and variability*

Function	Output	Variability
Landing in Stockholm/Arlanda	Park aircraft at gate 2	
Overnight Inspection	Report results of inspection	
	Ensure aircraft adequate condition	Imprecise
Review Meteorological Data	Provide meteorological data	
Provide Training	Provide training & competence	Imprecise
Pre-Flight Planning	Provide planning	
	Provide Time	
	Provide flight release document	
Provide Instructions & Guidelines	Provide operational instructions & guidelines	Imprecise
Provide Resources & Equipment	Provide appropriate resources & Equipment	Imprecise
Regulations & Supervision	Provide supervision & organizational guidelines	Imprecise
Civil Aviation Authority Control	Provide supervisory bodies to control SAS operations	
Provide Aircraft Information	Provide technical & operational information	
Facilities & Maintenance	Provide adequate facilities	Imprecise & too late
Prepare Aircraft for Departure	Aircraft ready for departure	Imprecise
ATC Clearances	Provide clearance for deicing	
	Provide taxi clearance	Imprecise
	Provide taxi time	Too late
	Provide takeoff clearance	
	Provide takeoff time	
Pre-Deicing Inspection	One-step procedure	Imprecise
	Two-step procedure	
	No deicing required	
Deicing	Perform deicing	Imprecise
Post Deicing Inspection	Aircraft is clean	Imprecise
	Aircraft is not clean	
Anti-Icing	Perform anti-icing	
Taxi Briefing/Checklist	Provide taxi briefing & checklist	
Taxi to Runway	Ready for takeoff	Imprecise & too late
Pre-Takeoff Inspection/Checklist	Provide pre-takeoff inspections & checklist	Imprecise
	Takeoff if within HOT & aircraft is clean	
	Return to gate if HOT is exceeded or aircraft is not clean	
Takeoff		Imprecise & too late

The clear ice issue was not mentioned in the training documents for the MD-80 pilots. The equipment for aircraft inspection was inadequate and did not facilitate the on-wing tactile inspection. The function "Overnight Inspection" received an imprecise control aspect provided by the function "Provide Instructions & Guidelines". The instructions did not require the flight technician to report his detection of clear ice during the overnight inspection to the mechanic responsible for deicing. The function "Pre-Deicing Inspection" received an imprecise control aspect provided by the function "Provide Instructions & Guidelines", an imprecise precondition by the function "Provide Training" and an imprecise resources aspect by the function "Provide Resources & Equipment". The PIC did not ask about clear ice during the conversation with the mechanic. The mechanic performed an inadequate inspection by climbing the ladder and only checking the forward part of the left wing with his hand and the air inlet of the left engine. The function "Deicing" received imprecise control aspects provided by the functions "Provide Instructions & Guidelines" and "Post Deicing Inspection", an imprecise precondition by the function "Provide Training" and an imprecise input by the function "Pre-Deicing Inspection". The deicing application failed to remove the clear ice at the roots of the wings. The deicing technician saw one indication tuft moving out of four and did not report further his observation. The function "Post Deicing Inspection" received an imprecise control aspect provided by the function "Provide Instructions & Guidelines", an imprecise precondition by the function "Provide Training", an imprecise resources aspect by the function "Provide Resources & Equipment" and an imprecise input by the function "Deicing". The mechanic did not inspect the wings again after deicing for clear ice since he assumed none existed. The function "Prepare Aircraft for Departure" received an imprecise control aspect provided by the function "Provide Instructions & Guidelines" and an imprecise input by the function "Overnight Inspection". The air intakes of the aircraft engines were not covered during the night as required. The function "ATC Clearances" received an imprecise and late input by the function "Facilities & Maintenance". The aircraft departure was delayed and the aircraft crossed a strip of slush while taxiing out. The function "Taxi to Runway" received an imprecise and late resources aspect by the function "Facilities & Maintenance" and imprecise preconditions by the functions "Post Deicing Inspection" and "Prepare Aircraft for Departure". The aircraft taxied eventually with clear ice on the wings without adequate inspection of the aircraft surfaces or protecting the engine inlets from slush. The function "Pre-Takeoff Inspection/Checklist" received an imprecise control aspect provided by the function "Provide Instructions & Guidelines". The aircraft was assumed clean and a rolling takeoff was performed. No further inspection of the wings was performed. The function "Takeoff" received an imprecise and late input by the function "Taxi to Runway" and imprecise precondition by the function "Pre-Takeoff Inspection/Checklist". The result was an inadequate takeoff with contaminated surfaces.

5. Discussion & Conclusions

The official accident report published by the SHK in 1993 stated that "*the accident was caused by SAS' instructions and routines being inadequate to ensure that clear ice was removed from the wings of the aircraft prior to takeoff*" (SHK 1993). The aircraft was inspected and deiced prior to takeoff and the inspection failed to detect the existence of clear ice. Clear ice can form on chilled wings under conditions of high humidity or precipitation. The primary concern about clear ice is the difficulty to detect it on the aircraft surfaces. Tests under realistic environmental conditions have shown that humans were not able by visual inspection to detect ice sheets less than 0.8 mm and complete ice films less than 1mm on white surfaces (Sierra et al. 2006). The visual inspection in case of clear ice would not be sufficient and a thorough tactile inspection is far more effective and becomes necessary (Sierra et al. 2006). Performed usually by deicing technicians, the tactile inspection is accomplished by sweeping the palm of the hand on the aircraft surfaces and using the tips of their fingers for a more in-depth checking (Eyre 2002). The environmental and work conditions present at the times of the pre-deicing and post-deicing inspections can affect the performance of the workers adversely. The degree of effectiveness and aspects of aircraft tactile and visual inspections for ice, snow and frost should be addressed in more in-depth studies to provide more effective inspection procedures.

The results of the FRAM analysis in this study provided a better understanding for the development of the accident as a result of the combinations of functional variability. The scope of this paper does not allow going further into all details of the analysis. Additionally, the data provided for this analysis was limited, since this study is conducted many years after the accident and it only depended on the information provided by the SHK accident report. The accident report provided a thorough investigation listing all findings and conclusions about the reasons that lead to the accident. The application of the FRAM analysis is beneficial through the provision of a new perspective on the conditions and circumstances before and at the time of the accident. To clarify, in addition to the inadequate SAS instructions, the analysis linked other events as well through the functional couplings to the accident such as the overnight inspection (leaving the engines' inlets uncovered) and the airport facilities (slush strip crossing during taxi). Relying exclusively on the accident report, it is not possible to determine how effectively those factors contributed to the accident. Nonetheless, to learn lessons for better performance and outcomes, those sources of potential variability were addressed, which would consequently enable a better variability management.

6. References

Eyre FW (2002) Tactile inspection for detection of ice on aircraft surfaces – notes on current practice. Transports Canada, Report No. TP 13858E, 2002. Accessed November 1, 2017. http://bibvir2.uqac.ca/archivage/17100950.pdf.

Hollnagel E (2012) FRAM, the functional resonance analysis method: modelling complex socio-technical systems. Ashgate Publishing, Ltd.

Leveson N (2011) Engineering a safer world: Systems thinking applied to safety. MIT Press.

SHK, Swedish Board of Accident Investigation (1993) Report C 1993:57 Air Traffic Accident on 27 December 1991 at Gottröra, AB county Case L-124/91. Stockholm, Sweden. Accessed November 1, 2017. http://www.havkom.se/assets/reports/English/C1993_57e_Gottrora.pdf.

Sierra EA Jr, Bender K, Marcil I, D'Avirro J, Pugacz E, Eyre F (2006) Human Visual and Tactile Ice Detection Capabilities under Aircraft Post Deicing Conditions, DOT/FAA/TC-06/21. Accessed November 1, 2017. http://www.tc.faa.gov/its/worldpac/techrpt/tc06-21.pdf.

Transport Canada (2004) TP 10643E - When in Doubt... Small and Large Aircraft- Aircraft Critical Surface Training for Aircrew and Ground crew. 7th Edition. 138 pages. Accessed November 1, 2017. http://www.tc.gc.ca/Publications/en/tp10643/pdf/hr/tp10643e.pdf

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