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Analysis of Comair flight 5191 with the Functional Resonance Accident Model

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Abstract

The goal of an accident investigation is to determine why a certain combination of conditions, events, and actions led to the specific outcome. Accidents in complex high risk operations, such as aviation, are frequently explained as the result of system failures, but few methods exist that can adequately be used to investigate how the variability of individual, technical, and organisational performance in combination may lead to an adverse outcome. The Functional Resonance Accident Model (FRAM) provides an approach to identify these elements and determine their interrelationship. This paper presents the principles of FRAM and illustrates how it was used to analyse a highly publicized aviation accident, the crash of Comair Airlines (Delta Connection) flight 5191 in Lexington, KY on August 27th, 2006. The use of FRAM provided details that were not found in the NTSB analysis and as such this approach model may help future investigations better elucidate causal factors and yield improved safety recommendations.

Introduction

The goal of any accident investigation is to determine why a certain combination of conditions, events, and actions led to the specific outcome. There are normally few problems determining what happened, since in most industrial domains the consequences are manifest. (The situation may not be the same for "accidents" in other fields of endeavour, for instance financial markets.) But the explanation of why something happened may be less obvious. In order to construct an explanation it is necessary to have a methodical approach, which in turn requires an articulated accident model or accident theory, i.e., a formal or semi-formal description of how accidents occur, often in terms of cause-effect relations.

Since the systematic concern for industrial accidents began about 100 years ago, practitioners and researchers have developed several different accident models and methods to help them in accident investigation. Such models and methods are usually adequate for the typical problems of their time; indeed, there would be little reason to develop models and methods that were more complex or powerful than needed. Yet because socio-technical systems continue to develop and thereby become more complex and more tightly coupled, all models and methods will eventually become outdated and underpowered.

Models have over time gone from simple linear models, such as the domino model (Heinrich, 1931), via complex linear or epidemiological models, such as the Swiss cheese model (Reason, 1990), to systemic models (e.g., Leveson, 2004). Despite their differences, they all adhere to the principle that accidents are caused and that the causes can be understood as failures or malfunctions of technology, humans or organizations – either alone or together. It has only recently become accepted that accidents can be the outcome of unexpected combinations of normal performance variability, i.e., arise from normal actions. This view recognizes that normal actions never can be completely prescribed or regulated because working conditions always are underspecified. Short and longer term adjustments are therefore needed to match specific situations or conditions. This variability is not just normal and useful, but indeed necessary for work to be done. On the individual level the adjustments have been described as sacrificing decisions or efficiency-thoroughness trade-offs (Hollnagel, 2004). On the collective or organisational level, the adjustments have been described using terms as drift or migration (Cook & Rasmussen, 2005). Since the variability normally is useful it mostly goes

unnoticed, regardless of the level at which it takes place. It is only when the variability gives rise to unexpected outcomes that it is noticed and deemed to be bad and a cause of failures.

Although many different accident models exist, the accident investigation community has yet to adopt one that is able to explain how the fundamental interrelationships among system functions may lead to adverse outcomes. This is nevertheless important if we are ever to change from a reactive to a proactive safety management. The Functional Resonance Accident Model (FRAM) and the associated method provide a way to examine individual system functions and determine their interrelationship. This paper reports the application of the FRAM to analyse a highly publicized aviation accident, the crash of Comair flight 5191 in Lexington, KY on August 27th, 2006. The goal of this application was to see what relationships the use of FRAM would discover as compared to how the investigation was performed in the traditional sense.

Comair flight 5191

At 0606 hours the morning of August 27th, 2006, Comair flight 5191 a Canadair 50 seat Regional Jet (CRJ) crashed after an attempted takeoff from the Lexington Blue Grass Airport in Lexington, KY. The flight was a 14 CFR Part 121 passenger revenue flight from Lexington (KLEX) to Atlanta, Georgia (KATL). The aircraft taxied out uneventfully and then inadvertently proceeded to depart from the shorter general aviation runway (runway 26) as opposed to the longer air carrier runway (runway 22). The aircraft became momentarily airborne after it struck an earthen berm, then collided with trees, and crashed. There was a significant post-crash fire consuming most of the aircraft, and 49 of the 50 passengers and crew perished. Figure 1 shows an aerial view of the Lexington Blue Grass Airport with an overlay of the aircraft's actual taxi route, the intended taxi route and the former taxi route prior to airport construction.

The NTSB investigation of the accident concluded that:

> ... the probable cause of this accident was the flight crewmembers' failure to use available cues and aids to identify the airplane's location on the airport surface during taxi and their failure to cross-check and verify that the airplane was on the correct runway before takeoff. Contributing to the accident were the flight crew's nonpertinent conversation during taxi, which resulted in a loss of positional awareness, and the Federal Aviation Administration's (FAA) failure to require that all runway crossings be authorized only by specific air traffic control (ATC) clearances.

The accident was explained as being caused mainly by the failures of the humans at the sharp end, with some blame also going to the Federal Aviation Administration (FAA). The remainder of this paper will illustrate how a FRAM analysis can produce a more nuanced – and therefore hopefully also a more adequate – explanation.

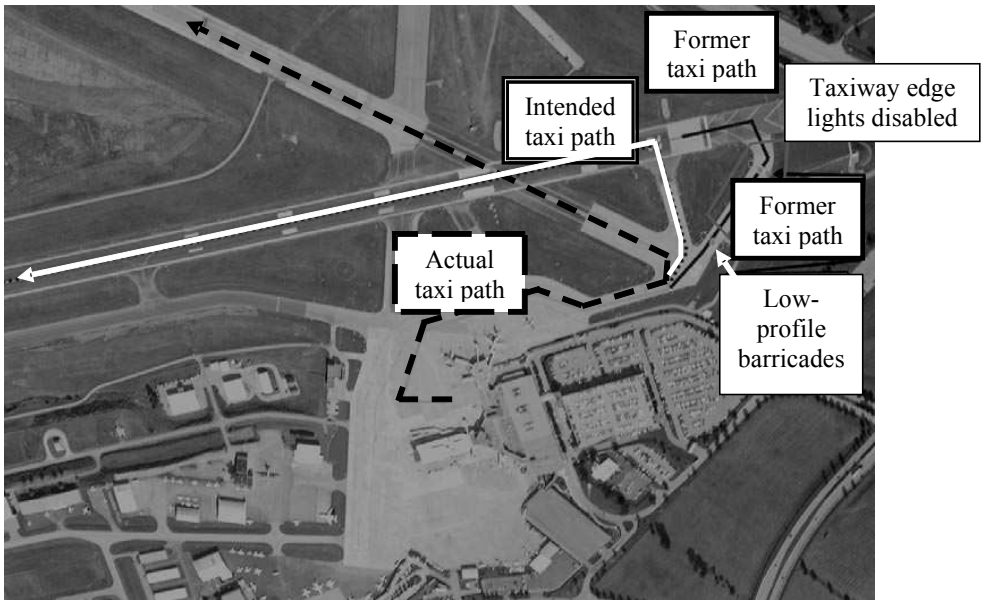

Figure 1: Comair flight 5191: Actual, intended, and former taxi paths.

Overview of the Functional Resonance Accident Model (FRAM)

The Functional Resonance Accident Model and the associated method provide a way to describe how multiple functions and conditions can combine to produce an adverse outcome (Hollnagel, 2004). FRAM is based on the following principles:

- *The principle of equivalence of successes and failures*. FRAM adheres to the resilience engineering view that failures represent the flip side of the adaptations necessary to cope with the real world complexity rather than a failure of normal system functions. Success depends on the ability of organisations, groups and individuals to anticipate risks and critical situations, to recognise them in time, and to take appropriate action; failure is due to the temporary or permanent absence of that ability.
- *The principle of approximate adjustments*. Since the conditions of work never completely match what has been specified or prescribed, individuals and organisations must always adjust their performance so that it can succeed under the existing conditions, specifically the actual resources and requirements. Because resources (time, manpower, information, etc.) always are finite, such adjustments are invariably approximate rather than exact.
- *The principle of emergence*. The variability of normal performance is rarely large enough to be the cause of an accident in itself or even to constitute a malfunction. But the variability from multiple functions may combine in unexpected ways, leading to consequences that are disproportionally large, hence produce a non-linear effect. Both failures and normal performance are emergent rather than resultant phenomena, because neither can be attributed to or explained only by referring to the (mal)functions of specific components or parts.
- *The principle of functional resonance*. The variability of a number of functions may every now and then resonate, i.e., reinforce each other and thereby cause the variability of one function to exceed normal limits. The consequences may spread through tight couplings rather than via identifiable and enumerable cause-effect links, e.g., as described by the *Small World Phenomenon*. This can be described as a resonance of the normal variability of functions, hence as functional resonance. The resonance analogy emphasises that this is a dynamic phenomenon, hence not attributable to a simple combination of causal links.

FRAM Functions and Aspects

In the context of an accident investigation using FRAM, the explanation is produced by proceeding through the following steps.

1. Identify essential system functions, using normal or accident-free performance as a baseline. This step characterises each function separately but does not try to arrange or order them in any way. The starting point may be existing task analyses, procedures, expert knowledge, etc. The characterisation uses the following six aspects:

- Input (I): that which the function processes or transforms or that which starts the function,
- Output (O): that which is the result of the function, either an entity or a state change,
- Preconditions (P): conditions that must be exist before a function can be executed,
- Resources (R): that which the function needs or consumes to produce the output,
- Time (T): temporal constraints affecting the function (with regard to starting time, finishing time, or duration), and
- Control (C): how the function is monitored or controlled.

Each function may be described by a simple table, which then can be used for the further analysis. It is also possible to show the functions graphically using a hexagon to represent each function (FRAM modules, Figure 2).

Characterise the observed variability of system functions, considering both actual and potential variability. The purpose of FRAM is to provide an explanation of the accident in terms of combinations of performance variabilities. The second step is therefore for each function to describe the actual variability during the accident. This may point to other functions that must be characterised as part of the explanation. For instance, if the input to a function came too late, or was of the wrong kind, then the source of that input – i.e., another function – must be described and characterised. This may in turn require yet other functions to be described, until the total scenario has been accounted for.

3. Identify and describe the functional resonance from the observed dependencies / couplings among functions and the observed performance variability. The output of the first and the second steps is a list of functions each characterised by two or more of the six aspects. (Notice that a function may require several instances of an aspect to be described.) The dependencies among functions can be found by matching or linking their aspects. For example, the output of one function may be the input to another function, constitute a resource, fulfil a pre-condition, or enforce a control or time constraint. The result is an overall description of how the functions were linked or coupled in the accident scenario, and therefore of how functional variability propagated through the system. In general, the links specify where the variability of one function may have an impact, or how it may propagate. Many such occurrences and propagations of variability may create a resonance effect: although the variability of each function may be below the normal detection threshold, they may in combination become a 'signal', hence constitute a risk.

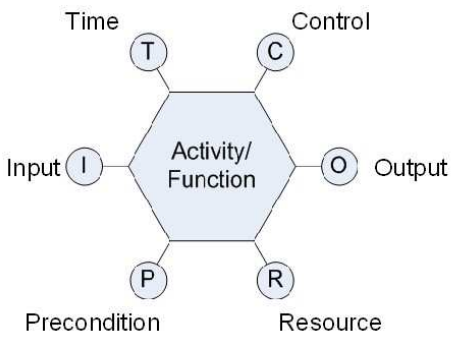

Figure 2: A FRAM module describing an activity or function in terms of six aspects.

This step may be supported by a visualisation of how the functions are linked. The visualisation can be valuable in tracing functional dependencies, but the analysis should nevertheless be based on the description of the functions rather than on the graphical representation.

4. Identify barriers for variability (damping factors) and specify required performance monitoring. Barriers are means to prevent an unwanted event from taking place, or to protect against the consequences of an unwanted event (Hollnagel, 2004). Barriers can be described in terms of barrier systems (the organizational and/or physical structure of the barrier) and barrier functions (the manner by which the barrier achieves its purpose). The four fundamental barrier systems are: (1) physical barrier systems that block the movement or transportation of mass, energy, or information; (2) functional barrier systems that set up pre-conditions that must be met before an action (by human and/ or machine) can be undertaken; (3) symbolic barrier systems that are indications of constraints on action that are physically present; and (4) incorporeal barrier systems that are indications of constraints on action that are not physically present.

Besides recommendations for barriers, a FRAM analysis can provide the basis for recommendations on how to monitor performance in order to detect excessive variability. Performance indicators may be developed both for functions and for the couplings between them.

FRAM analysis

The first step of the FRAM accident analysis is to describe the functions that make up the normal departure routine. For a typical civilian flight some of these may include:

- Review of weather and airport data,
- Taxi briefing,
- Takeoff briefing,
- Clearance(s) from ATC,
- Perform a taxi checklist,
- Taxi to runway,
- Perform a before takeoff checklist,
- Turn onto the runway,

- Takeoff.

The functions should include all those needed to begin the analysis. It is, however, not necessary to begin with a complete list. The analysis may identify further functions to be included, and since the functions are not ordered, e.g., in a sequence or a hierarchy, functions can easily be added or removed at a later time.

To illustrate the principle, consider the function *Review of weather and airport data*.

> All US air carrier flights are operated under regulations which require that a certified dispatcher and the captain assume joint responsibility for all pre-flight planning and preparation. Typically, a certified dispatcher will prepare and include all relevant flight information in the form of a flight release document for the crew to review. Additional information usually includes any applicable Notice to Airmen (NOTAMs) which describe changes at the departure and arrival airports or any navigational sources to be used during the flight that have not yet been included in charts or other sources of information. The investigation found no evidence that captain did not review this material.

The FRAM analysis normally continues by describing the other functions in the same way. Here we will, however, proceed to look at whether there was any variability in the way that the *Review of weather and airport data* was carried out in the accident.

> One NOTAM describing a portion of a taxiway closed due to construction (taxiway Alpha North of runway 26) was missing from the flight release. This section of taxiway was an important consideration because it changed the taxi route that the pilots were accustomed to.
>
> An additional source of NOTAM information regarding taxiway closures was the pre-recorded Automatic Terminal Information Service (ATIS). This recorded message by air traffic control contains current weather, runways in use and any relevant NOTAMs for the airport. Pilots listen to this broadcast on a specific radio frequency. The NOTAM regarding the taxiway closure was not included in the ATIS broadcast on the morning of the accident as required. The investigation was unable to determine why the controller omitted this information from that specific recording.

Even this initial description of *Review of weather and airport data* makes clear that it depends on at least three other functions, and that at least two of these have a common source of information, cf. Figure 3. The analysis may be continued by looking at the other aspects of the function node, e.g., preconditions or resources, to get a better understanding of how the performance of this function depends on the work situation.

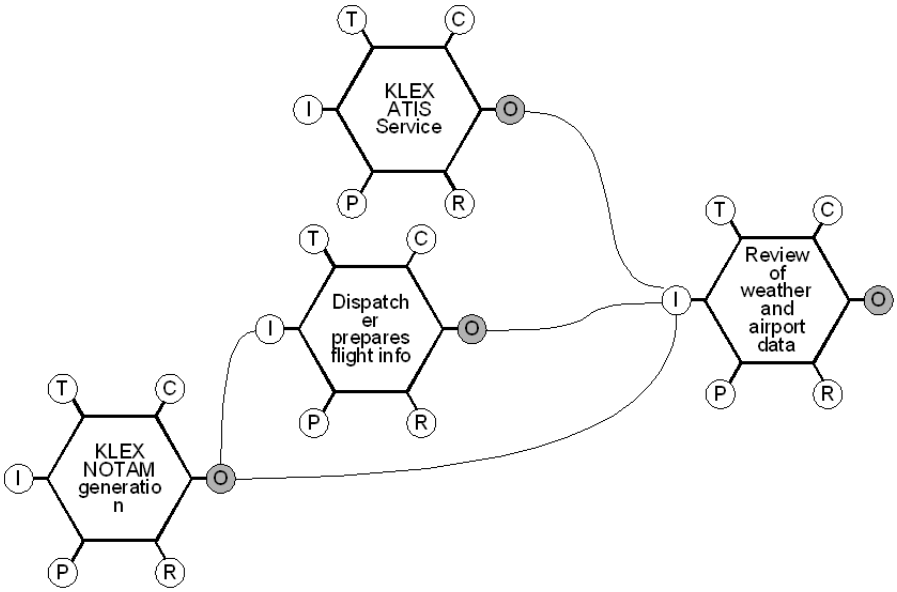

Figure 3: FRAM diagram for Review of weather and airport data *function.*

The accident investigation must obviously try to describe all relevant functions on a level of detail that makes it possible to explain the performance variability. For the purpose of illustration, it is reasonable

to focus on one function, *Taxi to runway*, to understand the factors and conditions that resulted in the aircraft being on runway 26 instead of runway 22.

> At 06:02 the first officer calls Lexington ground to request taxi clearance to the runway; seconds later ground control clears the flight to "*… taxi to runway two two altimeter three zero zero zero and the winds two zero zero at eight*." As part of this clearance, the controller is required to give the pertinent information from the new ATIS or require the flight crew to listen to the ATIS broadcast. The controller, however, did not realise that one NOTAM was missing, nor that it had been omitted from the ATIS.
>
> After the taxi checklist was completed the captain stated "*finish it up your leisure.*" This set a relaxed tone for the first officer to go through the before-takeoff checklist as he desired. Since this was the first flight of the day, there are several other items on the checklist, which therefore takes a little longer and requires the first officer to work "heads down" much of the time. Right after this there is about 40 seconds of social conversation, which the NTSB referred to as "*nonpertinent conversation*." This conversation took place where taxiway Alpha made several turns.

The above strongly suggests that *Taxi to runway* should not be described as one function but as several. But even a description on an aggregate level shows that *Taxi to runway* is rather tightly coupled to several other functions. Figure 4 provides an illustration of that.

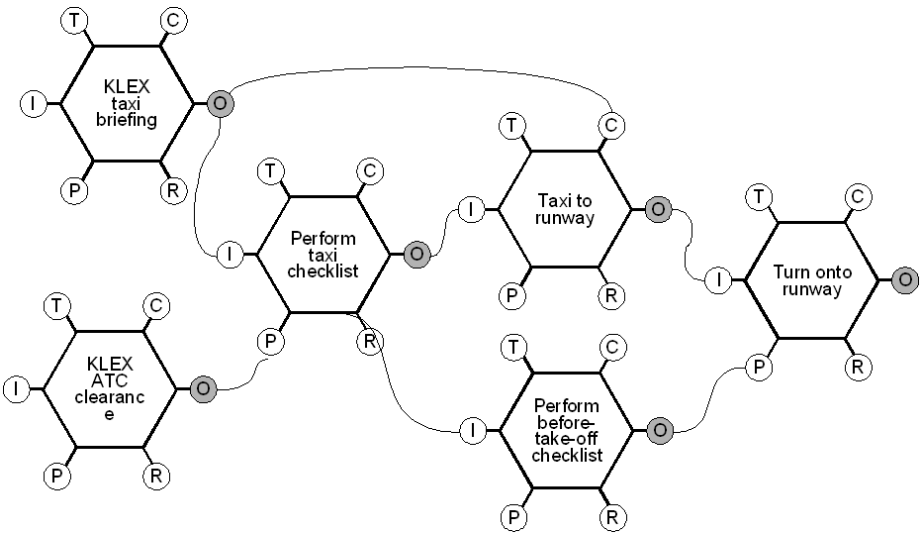

Figure 4: Taxi to runway

Going into a little more detail, Figure 5 is an excerpt from the surface chart the crew had available. It is significant to note that taxiway designation "A4" on the chart was marked on the airport surface with a sign that read "A6". This alone would make it difficult for the crew to detect any discrepancy between where they thought were and where they actually were.

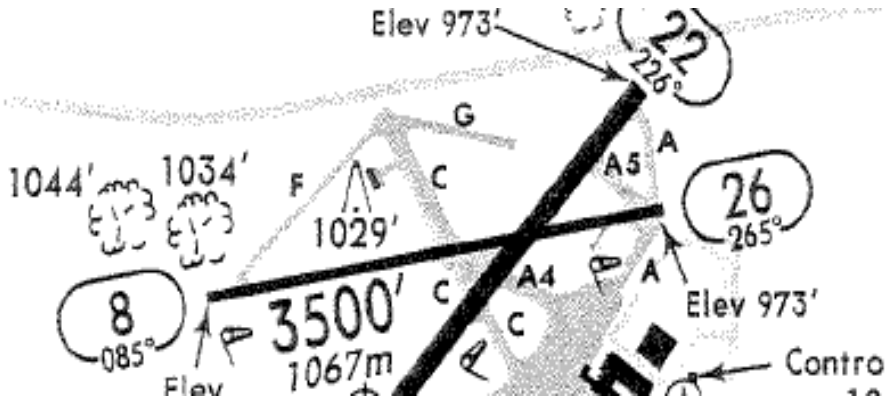

Figure 5: Lexington Jeppesen Chart. (Not for navigational use)

The before-takeoff checklist consists of 13 items only one of which is a challenge and response. The rest are action items for the first officer which must be verbally read when complete. This serves as a method to verify that all items were in fact accomplished. One item is the pre-takeoff announcement, where the first officer talked to the passengers over the intercom system. This took about 10 seconds to complete and occurred at the hold-short line for runway 26. Once this item had been completed, the first officer continued to finish the before takeoff checklist.

During the entire taxi to this point, the first officer was extremely busy with his required duties. When they arrived at the hold-short sign for runway 26, he apparently assumed that the captain had delivered them to the correct runway. The first officer was unable to see the red runway 26 sign to the left of the aircraft from his position in the cockpit's right seat. The height of the flight deck above the runway sign made it impossible for the first officer to see it once they were stopped at the hold short line impossible. At 06:05, the crew called ready for takeoff.

These aspects of ATC information and clearances can be seen as variability in the preconditions of the *Taxi to runway* function, incomplete charts as variability in resources, and the "*nonpertinent conversation*" as variability affecting controls of this function. The variability in visibility of taxiway markings, signs, and lighting affects the resources used in *Turn onto runway*. Another important source of variability was that only a single controller was performing all ATC tasks at Lexington at the time, affecting the time available for *ATC functions*. Lastly, obviously the preconditions of *takeoff* availability of sufficient length of unobstructed runway were not met, resulting in the output of achieving V1, rotation and climb out being unsuccessful. By making a similar analysis of other functions, a view gradually emerges of why the accident happened. Due to the size of the final analysis, it cannot be presented here, but Figure 6 illustrates the complexity of the situation and the level of detail that is needed to understand why the accident happened.

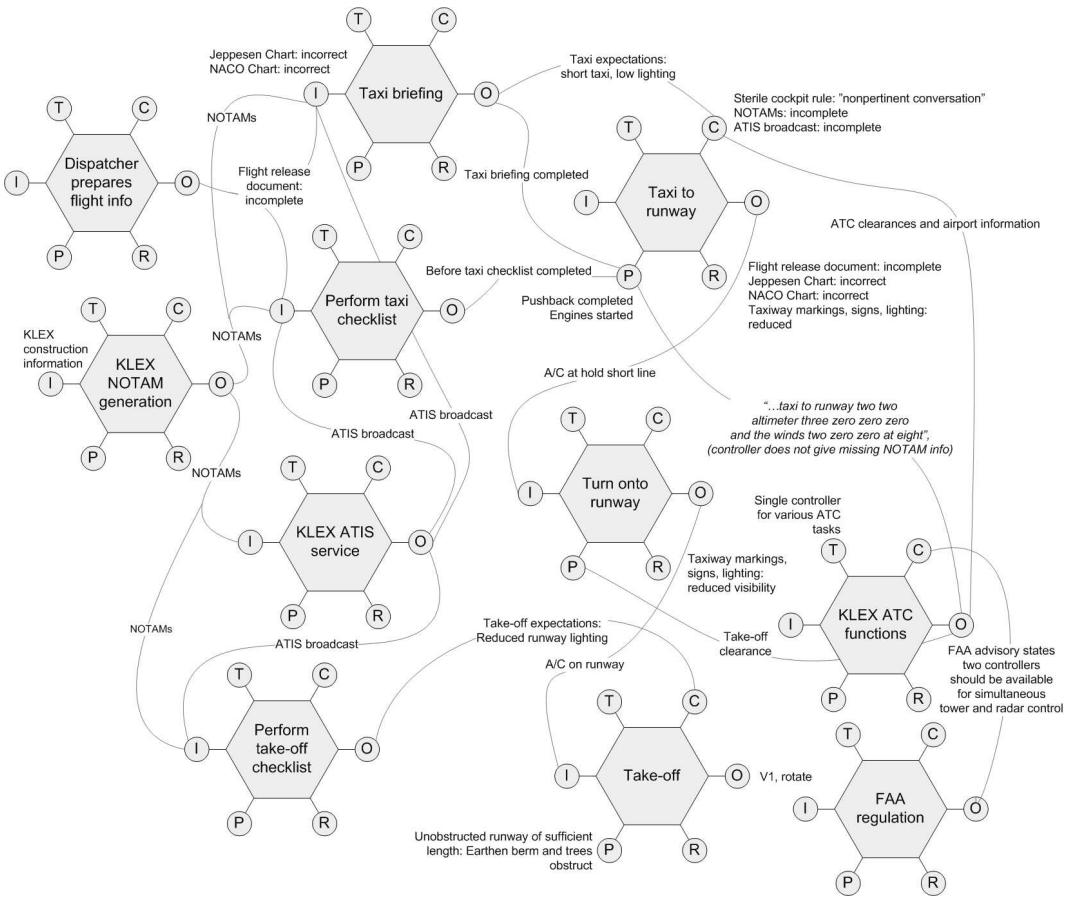

Figure 6: Important functions and couplings in the Lexington accident.

Summary and Conclusions

Although it is impossible to go through the complete analysis in this paper, the two functions described above illustrate how the FRAM method step-by-step builds up an explanation of the accident. Previous experience with FRAM has shown that it is often convenient to provide a graphical rendering of the analysis, such as shown in Figure 6. A simple software tool is available for this visual representation directly from the descriptions of the functions. It is, however, important to keep in mind that the substance of the analysis resides in the description and characterisation of the functions, and not in the resulting images.

The summary makes clear that the conclusions of the NTSB fall somewhat short of the mark by pointing to the failures of the flightcrew as the primary cause of the accident. As Figures 3, 4, and 6 demonstrate, the explanation cannot be reduced to a sequence of failures or mistakes, but must consider the situation and the conditions at the time as a whole, the lack of information, etc. The explanation is important for Step 4 of the investigation where appropriate countermeasures are developed, specifically how performance variability can be observed and dampened when needed. If the explanation is that the flightcrew did not follow procedures, then the obvious recommendation is to strengthen procedure compliance. In the case of this accident, the NTSB recommendations consist mainly of constraining performance to ensure procedure compliance and of improving information presentation in the cockpit as well as outside. The alternative, to manage performance and to control the sources of performance variability, is not considered.

As a method, FRAM has a clear theoretical grounding and is easy to learn and use. Since FRAM does not produce a simple sequential description, the administration of the analysis and of the findings can be time consuming. This can quite easily be alleviated by software tools; a prototype of these is already in use, and further developments are underway.

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