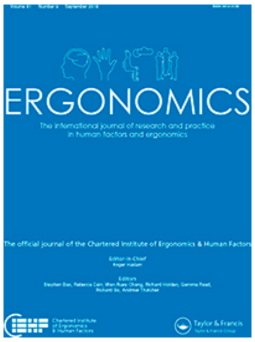

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A socio-technical analysis of functional properties in a joint cognitive system: a case study in an aircraft cockpit

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ABSTRACT
In a socio-technical work domain, humans, device interfaces and artefacts all affect transformations of information flow. Such transformations, which may involve a change of auditory to visual information & vice versa or alter semantic approximations into spatial proximities from instruments readings, are generally not restricted to solely human cognition. This paper applies a joint cognitive system approach to explore a socio-technical system. A systems ergonomics perspective is achieved by applying a multi-layered division to transformations of information between, and within, human and technical agents. The approach uses the Functional Resonance Analysis Method (FRAM), but abandons the traditional boundary between medium and agent in favour of accepting aircraft systems and artefacts as agents, with their own functional properties and relationships. The joint cognitive system perspective in developing the FRAM model allows an understanding of the effects of task and information propagation, and eventual distributed criticalities, taking advantage of the functional properties of the system, as described in a case study related to the cockpit environment of a DC-9 aircraft.

Practitioner Summary: This research presents the application of one systemic method to understand work systems and performance variability in relation to the transformation of information within a flight deck for a specific phase of flight. By using a joint cognitive systems approach both retrospective and prospective investigation of cockpit challenges will be better understood.

Abbreviations: ATC: air traffic control; ATCO: air traffic controller; ATM: air traffic management; CSE: cognitive systems engineering; DSA: distributed situation awareness; FMS: flight management system; FMV: FRAM model visualize; FRAM: functional resonance analysis method; GF: generalised function; GW: gross weight; HFACS: human factors analysis and classification system; JCS: joint cognitive systems; PF: pilot flying; PNF: pilot not flying; SA: situation awareness; SME: subject matter expert; STAMP: systems theoretic accident model and processes; VBA: visual basic for applications; WAD: work-as-done; WAI: work-as-imagined; ZFW: zero fuel weight

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FRAM; joint cognitive system; complex systems; abstraction hierarchy; systems ergonomics

1. Introduction

The term 'socio-technical' has been increasingly used since its first appearance in a 1950s seminal human-related research into coal mining sites (Emery and Trist 1960; Trist 1981; Trist and Bamforth 1951). A socio-technical system is a purposeful structure that consists of interrelated and interdependent social and technical elements influencing one another, directly or indirectly, to maintain their activity and the existence of the system itself to pursue its goal. Humans in a socio-technical system rarely work alone: they are always part of a group or an organisation, even though their actions may be separated in time and space. Therefore, for socio-technical systems, the need for both dual focus and joint optimisation of both human and technological symbiotic sub-systems was acknowledged early (Emery 1972).

A cockpit environment can be represented as a socio-technical system, where a number of agents are involved in everyday work, having different goals and tightly interacting tasks to ensure a safe and efficient flight (Chute and Wiener 2009). Complexity emerges because neither goals, nor resources, nor constraints remain constant, creating dynamic couplings between artefacts, operators and organisations. A complex system of people, equipment and procedures is involved to enable a flight to operate, requiring coordination between air traffic controllers, pilots, autopilots,

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aerodynamic surfaces, communication devices flight dispatcher, etc. (Palmer et al. 1991)

Following a socio-technical perspective, Cognitive Systems Engineering (CSE) has been developed to emphasise relationships among the system agents as a primary concern for analysing the work domain. CSE focuses on analysing how people manage complexity, understanding how artefacts are used and understanding how people and artefacts work together to create and organise Joint Cognitive Systems (JCS) which constitutes a basic unit of analysis in CSE. JCS emphasises the core idea of CSE that of co-agency: human and machine need to be considered together, rather than separate entities linked by human-machine interactions (Woods and Hollnagel 2006). The need to shift the classical cognitive science approach from the individual to a larger system, i.e. a JCS, becomes relevant in terms of examining the role of the material media in and physical processes that propagate representations across media (Hutchins 1995a).

This paper proposes an approach to identify distributed criticalities in terms of the propagation of tasks in a socio-technical system. The method pursued in this research is grounded in FRAM - Functional Resonance Analysis Method (Hollnagel 2012) as developed by Hollnagel. FRAM provides a method by which the underlying dynamics of socio-technical systems can be understood and revealed. In particular, FRAM enables the identification of critical interactions between functions and the system dynamics that emerge as a response to performance variability. This research extends classical use of FRAM to analyse the functional and structural properties of a distributed cognitive system, by use of an 'Abstraction/Agency', as originally proposed by Patriarca, Bergström, and Di Gravio (2017). The advantage of the Abstraction/Agency framework consists of allowing a deconstruction of the system at different levels of granularity. Rather than offering a hierarchical structural decomposition, as the original 'abstraction hierarchy' (Rasmussen 1985), or a hierarchical control structure, as for the Systems Theoretic Accident Model and Processes (STAMP) (Leveson 2004), the Abstraction/Agency is developed to support the analysts in the exploration of large socio-technical system properties. It supports back-and-forth inter-level (and/or intra-level) inter-agent intra-agent distributed functional analyses, rather than mono-directional hierarchical decompositions (Patriarca, Bergström, and Di Gravio 2017).

The adjective 'distributed' is used throughout this paper to highlight the relevance of interactions among people and artefacts (both natural and artificial) and the potentially consequential criticalities, emerging from analysing interactions rather than isolated components (Wilson 2014).

The proposed approach adopts a JCS perspective of the distributed work domain through FRAM; applied using the recently introduced Abstraction/Agency framework (Patriarca, Bergström, and Di Gravio 2017). Starting from the seminal work of Hutchins (Hutchins 1995a), this paper presents the JCS of a cockpit environment of a commercially operated aeroplane, in this case the Douglas Aircraft DC9 (DC-9) as the unit of analysis in order to show the distributed criticalities of the cockpit system performing its cognitive tasks of computing and remembering speed configuration. Therefore, each transformation of task-relevant information into its subsequent form or physical state was systemically analysed with the help of FRAM functions.

The paper is organised as follows. Section 2 clarifies the state of the art, from an analysis of literature related to JCS and FRAM. Section 3 details the research method developed in this study, specifying the building steps of the approach. Section 4 presents the case study of a DC-9 cockpit with two examples to clarify the potential of the approach. A discussion section summarises the outcomes of the study and lastly the conclusions provide the implications of the proposed approach in human factor related research.

2. Motivation for the study: a literature review

This section contextualises the proposed approach in the current literature on JCS. It also outlines the possibility to combine the FRAM with a JCS perspective, taking advantage of the recently introduced framework, i.e. the Abstraction/Agency framework (see Patriarca, Bergström, and Di Gravio 2017).

2.1 About the joint cognitive system

JCS acknowledges that cognition emerges as goal-oriented interactions of people and artefacts in order to produce work in a specific context, and at the level of the work being conducted (Bergström and Dekker 2014; Hollnagel and Woods 1983; Hutchins 1995a, 1995b). It does not produce models of cognition, but models of co-agency that correspond to the requisite variety of performance (Woods and Hollnagel 2006) and thereby emphasises the functional aspects, i.e., what a system does rather than how it does it.

In his 1995 case study 'How a cockpit remembers its speeds', Hutchins put this into practice by emphasising that researchers have easier access to the representations available in the cockpit, than to the representations that result from processes that operate within individual 'human' actors. Hutchins descriptions (Hutchins, 1995a) showed that the representations of memorised landing speeds generated by the joint cockpit system are not necessarily the ones retained in the pilots' working memories. In JCS 'coordination must be analyzed as a distributed phenomenon emerging from the interactions between people and artefacts' (Bergström et al. 2011). In a sequel to Hutchins' paper, (Henriqson et al. 2011) an ethnographic study of 22 events involving failures related to the calculation of take-off speeds concluded that from a co-agency perspective, human cognition or sense making can only be understood through understanding emergent phenomena of local interactions. Failures of coordination, lack of synchronisation and suboptimal understanding of cognitive distribution between practitioners or between practitioners and artefacts often resulted in loss of joint control capacity (Henriqson et al. 2011), in many cases with aircraft or personal damage world. To clarify coordination, Hutchins used a description of representations and cognitive processes external to the pilots, in which memory processes may be distributed among human agents, or between human agents and external representational devices. Information about speed is in some sense the 'same' information whether it is represented in spoken words, aural sounds, as a string of written characters on a flight plan or as semantic interpretation of an airspeed indicator (Palmer et al. 1991). Accordingly, in this paper we systemically analyse each transformation of task-relevant information into its subsequent state from a functional perspective and apply the principle of agent-neutrality (Adriaensen et al. 2017b), in which we abandon the traditional boundary between medium and agent. By giving equal weight to systems, artefacts, human agents and even environmental actors, as well as by applying a breakdown of FRAM functions into its smallest significant parts, the flow of transformation of representations in the cockpit corresponded to the propagation of tasks for this specific work analysis. We focus on cockpit choreography as the unit of analysis.

The approach in this paper differs from the classic Situation Awareness (SA) theories where operators are primarily responsible for understanding present and future states of their system behaviour, but designers are responsible for creating the best circumstances to achieve this (Endsley 1995; Salas et al. 1995). Sarter and Woods (1991) described that the use of SA has become ubiquitous, but also that the principle is ill-defined. More evolved SA theories include Distributed Situation Awareness (DSA), where SA is an emergent property of collaborative systems. DSA has also been used to analyse transport system issues. One example, beinga DSA-based description of the events preceding the AF447 crash taking a JCS view that systems and not individuals loose SA (Salmon, Walker, and Stanton 2015). DSA can even be used to study normal work, in line with our study, as Sandhaland et al. (2015) did during bridge operations on platform supply vessels. DSA takes SA 'out of the heads of individual operators and on to the overall joint cognitive system consisting of human and technological agents' (Salmon, Stanton, and Jenkins 2009). DSA is the product rather than the sum of each individual's schema, in which the classic aim for individual's SA is abandoned (Salmon, Stanton, and Jenkins 2009), but teams are expected to still strive for compatible SA. Even DSA thereby uses mental constructs to explain system behaviour. A purely functional approach, like the one that was used in the research described in this paper, refrains from using mental constructs all together. Another motivation for applying FRAM was found in the fact that it allowed us to analyse functional resonance and information propagation between agents and artefacts of all kinds, without showing prejudice about a method that is focussed around one specific problem, keeping Hutchins' rich ethnographic analysis in mind. De Vries and Bligård (2019) provides an overview of modelling socio-technical and JCS systems by visualisation tools, including, but not limited to, FRAM.

2.2 About the use of FRAM

A complex work system is characterised by interdependent components with linear and non-linear interactions. Even small oscillations occurring in specific tasks may influence the behaviour of the entire system, leading to potentially critical consequences. Furthermore, the environment can be subjected to irregular and random external phenomena (Hollnagel 2014), contributing to increasing its inherent intractability. FRAM proposes a structured approach to gain an overall understanding of a system's functioning, emphasising a comprehensive view of the work domain by a formal description of system's functions and their interactions (Hollnagel 2012).

Even though FRAM has been applied to a number of different domains, it was originally developed in 2004 for accident analysis (the original acronym was Functional Resonance Accident Model), mainly in aviation. In this context, Sawaragi, Horiguchi, and Hina (2006) and Hollnagel et al. (2008) discussed the propagations of performance variability respectively in the flight of American Airlines flight 965 that crashed at Cali in Colombia in 1995 (Aeronautica Civil of the Republic of Colombia 1995) and the 2006 Comair Airlines flight 5191 crash in Lexington, Kentucky. The 1995 accident has recently been revisited (Hirose, Sawaragi, and Horiguchi 2016) integrating FRAM with fuzzy reasoning to model the effects of variability among equipment and humans. FRAM (subsequently labelled as the Functional Resonance Analysis Method) has also been used to define a set of domain specific safety performance indicators, with a focus on normal operation (Herrera, Hollnagel, and Håbrekke 2010), where nothing goes wrong. Focussing on normal operations, (De Carvalho 2011) showed how under normal variability conditions, the Air Traffic Management (ATM) systems (pilots, ATCOs, equipment, procedures (etc.) were not able to deliver an efficient flight monitoring function using feedback or feedforward strategies to achieve an adequate control of an aircraft flying in controlled airspace. The approach summarises the need for a deeper understanding of actual system functioning.

Evolutions of the traditional FRAM approach later proposed a semi-quantitative approach based on Monte Carlo simulation (Patriarca, Di Gravio, and Costantino 2017) to deal with the complexity of the aviation work domain. Rutkowska and Krzyżanowski (2018) provided another FRAM application for ATM by modelling the transfer of control over aircraft.

FRAM is appreciated as a useful tool to build an understanding of non-linear dependencies, performance conditions, variability and their resonance across functions (Herrera and Woltjer 2010). Even in different domains, FRAM has been used to understand the role of different agents and their respective and collective influence on the healthcare system (Pickup et al. 2017), proving the relevance to study the work-as-done under normal circumstances, again in healthcare (Clay-Williams, Hounsgaard, and Hollnagel 2015); or to consider the effects of changes in maritime operations (Praetorius, Hollnagel, and Dahlman 2015) and maritime mooring (Patriarca and Bergström 2017); or to replay how task fluctuations might propagate through everyday railway operations (Fukuda et al. 2016) and to model complex relations among railway system elements (Patriarca, Bergström, and Di Gravio 2017). These safety domains have very recently (Hulme et al. 2019) been acknowledged to be the common accident contexts in a review of other system thinking accident analysis applications from 1990 until 2018, which beside FRAM also cover AcciMap, HFACS, STAMP-CAST.

In this study, we aim to develop a FRAM model to understand the information flow propagation in a cockpit environment under normal conditions (everyday performance, work-as-done), following a JCS perspective. The latter would allow analysing how task-relevant information moves 'through the cockpit system by translating the representation of information in one medium to a representation in another' (Palmer et al. 1991).

2.3 About the use of the abstraction/agency framework

Work-as-done is a moving target of analysis since working conditions, scenario demands, and resources are rarely stable in everyday operations. In a complex working environment, the work becomes allocentric, rather than egocentric (Hollnagel 2017); work is tightly coupled by the actions of different agents acting based on their local rationality. The analysis of work should not only reflect individual reasoning, but rather acknowledge the difficulties arising when exploring the inter-relatedness among agents across levels. In this case, the FRAM model could easily generate an overwhelming representation. However, discussing Rasmussen's legacy for scientific visualisation in complex systems (Le Coze 2015), a single level of representation does not allow for describing and coping with different scenarios (Rasmussen 1985) whereas a multi-layered approach permits an analytical determination of the interrelatedness and independencies of the multiple layers, which can consist of both agents and abstraction levels. It becomes necessary to transfer the analysis to different levels of resolutions i.e. abstraction (or granularity). This assumption is in line with traditional FRAM theory, as inherently acknowledged by Hollnagel himself (2012), who argued for FRAM's scale-invariance, i.e. fractality.

In this path, we followed the recently introduced Abstraction/Agency framework for FRAM (Patriarca, Bergström, and Di Gravio 2017), evolving Rasmussen's classical Abstraction/Decomposition framework in line with modern socio-technical systems. Note that the Abstraction dimension defines the resolution at which the work domain is observed, while the Agency dimension relates each abstraction level to the agents involved in the system. As shown in the literature (Patriarca, Bergström, and Di Gravio 2017), the Abstraction/Agency framework allows managing the complexity of representation especially for highly inter-related systems, enhancing the representation of the work domain. In this paper, following a JCS perspective, we explore the possibility to analyse artefacts as agents on their own in order to understand the different propagation of tasks in a cockpit environment. Due to the writing constraints of this paper, we point to the literature for the previously described method (Patriarca, Bergström, and Di Gravio 2017) of applying an Abstraction/Agency framework to the classic FRAM model. See also section 3.5 from the research method to understand the application of the framework to this case study.

3. Research method

In this section, starting from FRAM principles, the steps developed for the purpose of the analysis of a cockpit as a joint cognitive system are described.

3.1 Starting from traditional FRAM

FRAM relies on four principles (equivalence of success and failures, approximate adjustments, emergence and functional resonance), as detailed in Hollnagel (2012). We adapted the four classic FRAM building steps (Hollnagel 2012) relying on a hexagon-based functional description. The methodological approach presented in the sub-sections 3.2–3.7 will be described through the case study presented in section 4. Additionally, the next sections will discuss how this study meets internal & external validity, reliability and objectivity, which in qualitative research as advocated by Anfara, Brown, and Mangione (2016) can be translated into credibility, transferability, dependability and confirmability.

3.2 Step 1.1: Develop a FRAM model for Work-As-Imagined (WAI)

The research question was defined iteratively to explore some varieties of human work, with the background of recent research trends that acknowledge the existence of multiple work dimensions, i.e. work-as-done, work-as-imagined, work-as-prescribed, work-as-disclosed (Moppet and Shorrock 2017).

Work-as-disclosed is related to what people say or write about work, showing its practical details; work-as-prescribed represents the formalisation of work practices by task-oriented (e.g. procedure, checklist) or job-oriented elements (e.g. job description, management system). Work-as-prescribed has limited variance with respect to work-as imagined, which is assumed to be the safe and right way to perform an activity. Based on this premise, but in line with previously mentioned research, this paper adopts the traditional lexicon, defining firstly a model for work as described in procedures and handbooks (labelling it Work-As-Imagined, WAI).

The Douglas Aircraft DC-9 flight crew operating manual and SAS DC-9 aeroplane flight manual represented the main sources for gathering a background knowledge of the process. One of the researchers (with a background as an aircraft pilot) facilitated the initial document analysis. Starting from the acquired background experience, two researchers developed a first FRAM model to describe work-as-imagined and started defining the functional resonance space, assigning abstraction levels and agents to the identified functions (Patriarca, Bergström, and Di Gravio 2017).

3.3 Step 1.2: Develop a FRAM model for Work-As-Done (WAD)

The four authors organised a two-day workshop with three pilots with flying experience of the DC-9 in order to gather operational information on the work domain. The aim of this focus group (four researchers and three pilots) was to develop a model of work-as-done, useful as a basis for further systemic analyses. During the workshop, the authors interviewed three Subject Matter Experts (SMEs) via informal interviews. Anfara, Brown, and Mangione (2016) argue for prolonged engagement in the field as one additional strategy for credibility in qualitative research. This was covered by the researchers' aeronautical experience, which encompassed a former airline pilot, a former air traffic controller, a risk engineering researcher with piloting licence and an aeronautical engineer. The credibility of reproducing data in a Work-As-Done (WAD) environment was strengthened by triangulating several sources such as realistic DC-9 cockpit training posters and congruency of opinion that enabled the pilots to reproduce their tasks and aircraft feedbacks. The pilot informants were asked to physically show the researchers their actions for this specific task on the cockpit posters, sometimes revealing and resolving inconsistencies in the narratives (see Figure 1). Different opinions and ambiguities were resolved by discussion or by challenging different scenarios in the model. WAI from manuals and company information served as a memory aid to remind the researchers how WAD differed from WAI. This choice acquired a crucial role for defining objectively the most complex parts of the process by a triangulation of sources and credibility and plausibility cheques, generating thus a

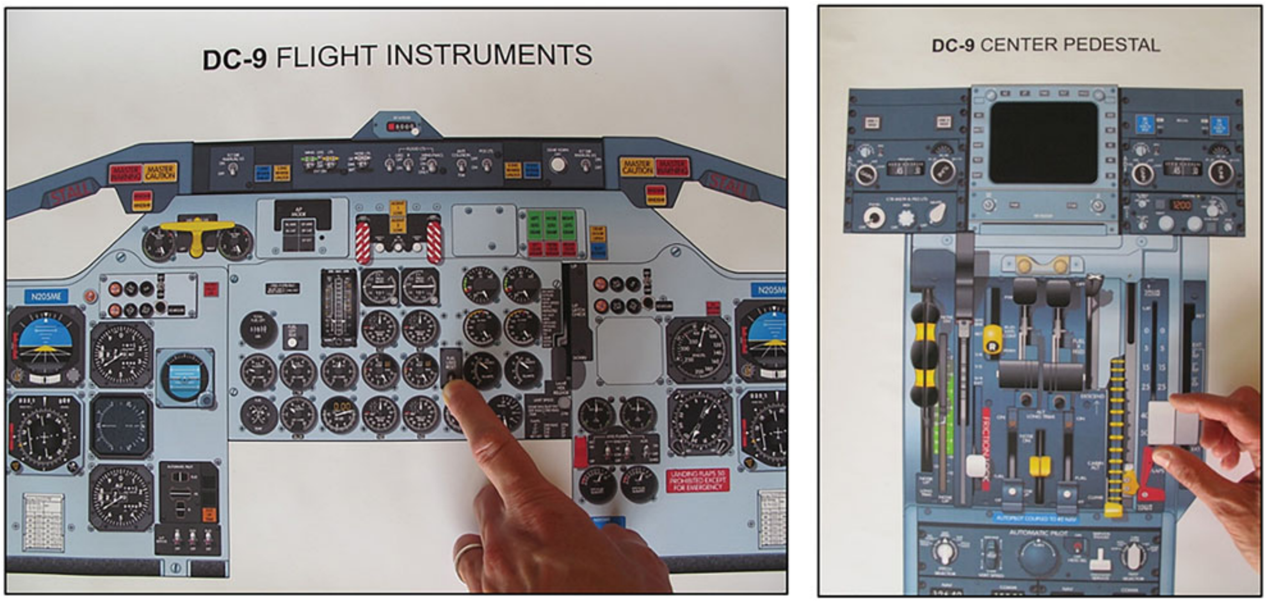

Figure 1. Printed supports for the analysis of the WAD FRAM model, developed in collaboration with three pilots.

shared overview of the work-as-done among the members of the focus group.

The flexible and conversational nature of interviews allowed a direct revision of the original FRAM model by one of the authors, who updated an Excel data entry form, automatically linked with the graphical representation of the model, via the IT tool myFRAM (Patriarca, Bergström, and Di Gravio 2017).

The full visualised hexagonal FRAM model for this case study can be consulted in Adriaensen et al. (2017b). In a last step, the data was presented at a FRAM conference Adriaensen, Bergström, and Di Gravio (2017) in a process that is generally known as dependability by qualitative researchers (Anfara, Brown, and Mangione 2016) to challenge critique from peers to increase reliability,.

3.4 Step 1.3: Check the completeness and consistency of the model

After the workshop, the model was checked for completeness and consistency, defining a final list of functions and respective aspects. The Excel data entry form acquired a pivotal role to perform systematic cheques and gain an in-depth systematic analysis of the work-domain. After gathering the data from the informants, a FRAM model will automatically reveal remaining conflicts in the description of functions or loose ends that need to be further elaborated. This research has been conducted using the MS Excel tool for FRAM analyses myFRAM[1] (Patriarca and Bergström 2017), in combination with FMV- the FRAM Model Visualiser. In particular, the model has been built in a tabular way using myFRAM (which relies on Visual Basic for Application, VBA) and then using its function for converting the model into a graphical representation to be read with FMV (Patriarca et al. 2018). This conversion graphically reveals any isolated functions that lack necessary in- or outputs until the researcher can accomplish a 'closed' model. Closing such a complex model forced the researchers to resolve remaining conflicts with the help of the informants.

3.5 Step 2: Identify performance variability

The purpose of this phase consists of characterising the potential actual variability of specific instantiations of the model for each function. This step is useful as a preliminary analysis to determine how functions can become coupled and how these can lead to unexpected outcomes. The outcome of the analysis was used to perform member cheques by which the credibility of the FRAM functions was checked by informant validation representing internal validity.

3.6 Step 3: Aggregate performance variability

Starting from the considered performance variability, at this step we started identifying which couplings potentially play a significant role during a dynamic operational scenario. In this step, relying on both the assigned performance variability and on the

Table 1. List of FRAM functions for each agent, following the Abstraction/Agency framework (colour representation related to Figure 3).

Pilot Flying (PF)	Pilot Not Flying (PNF)	Aircraft Systems	Aircraft Artefacts	Aircraft handling & aerodynamic response
PF manage performance data and aircraft status	**PNF manage performance data and aircraft status**	**Execution and feedback of pilot's tasks (Aircraft systems)**	**Support pilot's cognitive tasks (artefacts)**	**Aircraft responds to aerodynamics and handling**
Involve previous experience PF	Insert initial weights	Aircraft autopilot controls pitch and power	Provide easily detectable instrument cheques between PF-PNF	Aerodynamic behaviour
Set speed bugs PF	Involve previous experience PNF	Aircraft matches pilots speed input	Aircraft landing weight memory aid	Reduce speed 1st landing configuration changes
Cross check (spatial similarity) speed bugs with PNF	Calculate fuel to destination	Aircraft extends slats and flaps 5	Aircraft limitation data memory aid	Reduce speed for flaps 5
PF fly and navigate the aircraft	Calculate Gross Weight Flight Plan	Aircraft systems intercept ILS	Artefact matches weight and speeds	Approach Glide Path
React to dynamic traffic situation	Interpret correct Gross Weight	Aircraft extends flaps 15	Create visual indication to maintain Vth	Reduce Speed in relation to flaps 15
Select either manual flight or auto-pilot mode	Create distance/altitude algorithm	Aircraft lowers gear in response to pilot's inputs		Reduce Speed in relation to flaps 25
PF manages pitch and power	Determine top of descent	Gear down and locked		Reduce Speed in relation to flaps 40
PF targets speed	Confirm estimated Landing Weight	Aircraft extends flaps 25		Aircraft maintains Vth
PF selects vertical speed	Materialize landing weight calculations	Aircraft extends flaps 40		
Complete descent item landing weight and data from checklist	Correct landing weight calculations (contingencies)	**Support pilot's cognitive tasks (systems)**		
Maintain Speed between V_clean and 250 IAS	Set speed bugs PNF	Environment influences flight parameters		
Maintain Speed above V_clean	Cross check (spatial similarity) speed bugs with PF	Compute remaining fuel FMS		
Manage predefined pitch/power heuristics	**PNF support and monitor PF**	Aircraft displays operational data		
Adjust Thrust	Start descent item landing weight and data from checklist	Display Gross Weight (FMS)		
Change vertical speed	Callout V_clean passing 240 IAS	Create TOD visual indication to pilots		
Descent at managed rate and speed	PNF move flaps 5 position	Create visual indication of fuel parameters		
Approach intermediate fix	PNF lower gear	Aircraft provides indication of jammed slats and flaps position to pilots		
Request Flaps 5 to PNF	PNF move flaps 15 position	Aircraft systems shows flap split situation to pilots		
Confirm correct flaps and slats position in relation to handle position	PNF move flaps 25 position			
Confirm flaps and slats configuration	PNF Moves flaps 40 position			
Transform ATC vectors	PNF monitors PF in maintaining Vth			
Intercept localiser				
Intercept glideslope				
Request gear down by PF				
Request flaps 15 to PNF				
Request flaps 25 to PNF				
Request flaps 40				

Manufacturer Performance dpt	Joint Pilots	Flight Dispatch dpt	Air Traffic Controller (ATCO)	Procedures dpt	Relevant Time moment
Provide performance data that keep aircraft within safe envelope	**Joint Pilots team actions to manage safe flight**	**Prepare flight data (dispatch)**	**ATC control traffic**	**Develop unambiguous and rigid procedures (procedure dpt)**	**Relevant time moment**
Create performance test data	Pilots check Flaps 0 before flight	Prepare data by flight dispatch	ATC speed reduction	Procedures trigger pilot action	T-before flight (time moment)
Create weight-speed readout	Confirm presence of speed card booklet	Flight plan preparation	Clearance for a correct descent profile		T-during entire flight (time moment)
	Perform fuel cheques	Compute cargo and passenger weight	Clearance for additional vectors		T-cruise flight (time moment)
	Check expected fuel burn		ATC vectors for ILS approach		T-descent (time moment)
	Manage contingencies				T-approach (time moment)
	Cognitive confirmation of gear down and locked				T-intermediate approach (time moment)
	Perform landing checklist				T-final (time moment)
					T-final approach (time moment)
					T-short final (time moment)

connections' type (Input, Control, Precondition, Resource, Time), the potential combinations of variability were explored to understand how functional resonance might emerge. For this step, advantage was taken of the Abstraction/Agency framework to generate analyses at different granularity. In addition to the literature about Abstraction/Agency framework (Patriarca, Bergström, and Di Gravio 2017), we describe the framework applied to this case study. Table 1 provides a full overview of all the FRAM functions used (Function descriptions), grouped according their Generalised Function (GF), which is the first abstraction level, in other words the second level of the model. This level consists of specific descriptions of more general role agents. One can see that each column presents one agent, but that the agent is not necessarily restricted to performing single general roles. The Pilot Flying's (PF)[2] role of managing performance data and aircraft status is very different from the PF role of flying and navigating the aircraft. Another representation of the second level of all GF's (the Coloured boxes from Table 1) can be found in Figure 3. Level 1 with all the Physical Functions contains all the hexagons of the classic FRAM model (see Hollnagel 2012) and as previously depicted in Adriaensen et al (2017b). Confronting the data and methodology with peers at a FRAM conference reminded us that one should be mindful that abstraction levels should emerge from a bottom-up functional aim that serves the scope of the research under consideration, but also emerge from the data and not from researcher top down choices, differently from traditional hierarchical control structures.

When assessing the aggregation of performance variability, the results were compared against the outcomes from the Hutchins paper and the Henriqson et al. (2011) study with identical or similar task descriptions, but with a different methodology, being ethnographic observational and interview data and retrospective accident report analysis. This triangulation of outcomes increased our confidence in both results and the validity of the research. The pilots confirmed the significance of this study's methodology and the narratives that emerged from it.

3.7 Step 4: Manage performance variability

The purpose of this final step consists of suggesting ways to manage variability, damping or accepting or, if adequately controlled, amplifying. This step can be useful also to define specific performance variability indicators or strategies for optimising system design.

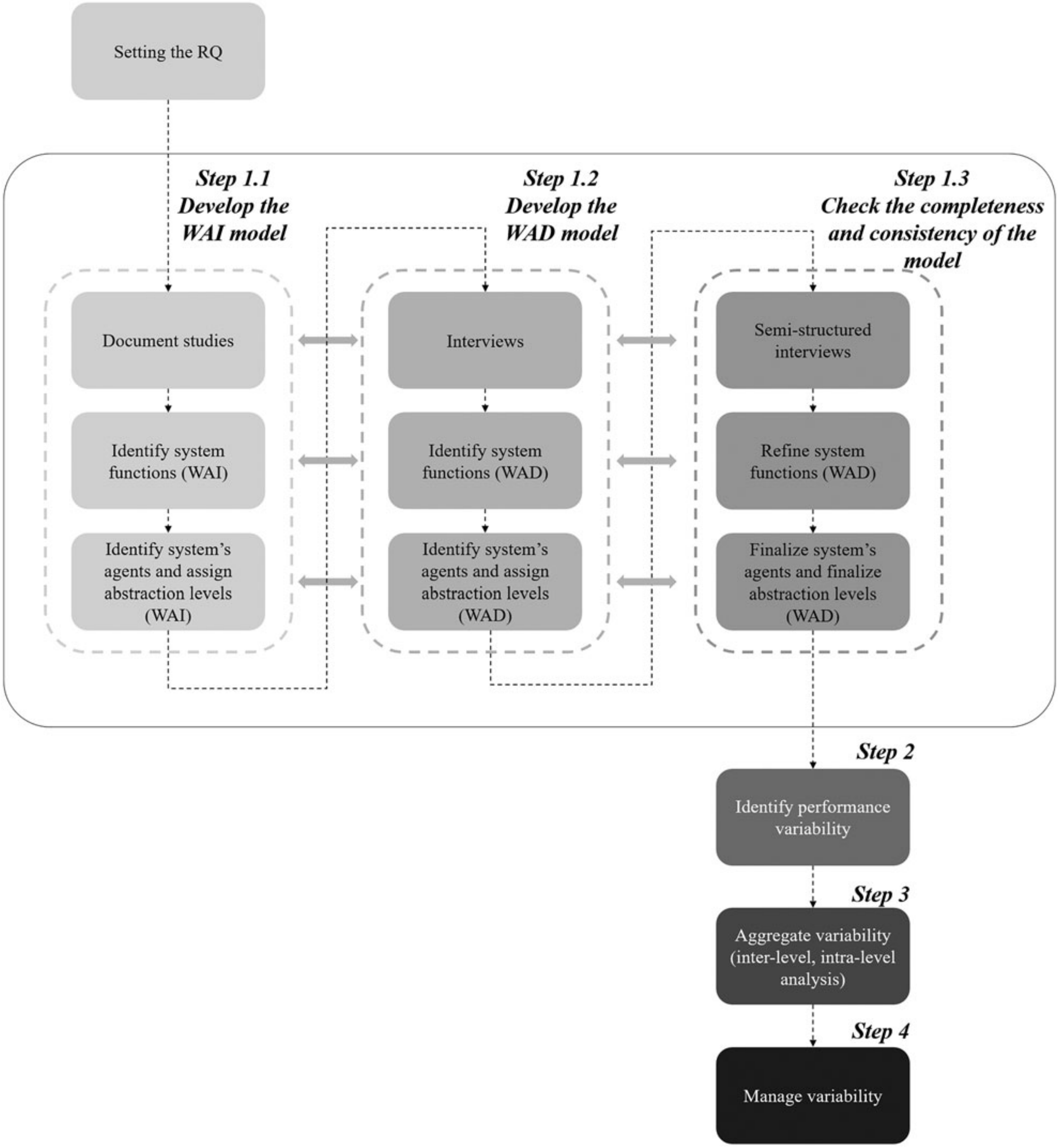

Figure 2. Steps of the research method developed in this research.

Figure 2 summarises the adopted methodological process.

4. Case study

This paper re-iterates Hutchins' (1995a) ideas of information flows, transformation of information and distributed information access during the speed reduction schedule of an aircraft for approach and landing, a scenario which Hutchins analysed from an ethnographical perspective.

4.1 How a DC-9 cockpit remembers its speed

The DC-9 aircraft was used because its operation is nearly identical to the MD-80 aircraft from the Hutchins' case, and because we found three DC-9 pilots from the same former airline, whereas the MD-

80 pilots didn't belong to the same company. A requirement to develop a consistent WAD model is a group of pilots that worked with the same company procedures. In addition, both aircraft have only early-generation automation only, and a well-understood cockpit design was a prerequisite to be able to control the cognitive choreography with physical artefacts, without adding layers of opaque automation from today's complex aircraft systems. We built and validated a functional model to cope with an earlier described socio-technical system, applied to an understandable scenario with low cockpit complexity. The substantial increase from today's system transformation flows, would expand the model's size and require additional researcher resources. This case study has been used to first establish a JCS approach to the application of FRAM that can generically be applied to other socio-technical systems by using transformation of information as the building blocks of the token or physical exchanges between agents in a multi-layered work analysis.

The scope of the FRAM model, being the specific task for analysis, was the choreography of reducing speed for landing, which comprises the process of calculating and memorising speeds and included activities that were influenced by speed settings - such as configuration changes - but not necessarily every action that takes place during the approach.

During the approach, the aircraft speed is reduced at incremental steps of flap extension and at one point also landing gear extension, each with their corresponding maximum operating speed. These speeds, including the final landing speed (Vth) depend on the aircraft's Gross Weight (GW), which is the sum of the Zero Fuel Weight (ZFW) and the remaining fuel. The ZFW on its turn is determined by totalling the aircraft's empty weight based on estimations of passenger and the cargo load, but without fuel.

The performance data is derived from different sources and in different forms: for example, the GW is calculated from the ZFW, in our case study pre-computed or written in the flight plan by flight dispatch, while the remaining fuel weight is derived from fuel gauges. The net result is a semantic number for the projected gross weight as expected at touchdown. This must be transformed into the landing speed for a certain weight, because landing speed, i.e. the approximate moment when lift is lost, varies with weight. On the DC-9 and on many other aircraft, the conversion from weight into speed is accomplished by a simple, but very effective artefact, i.e. a booklet of speed cards (Hutchins 1995a): 'The booklet contains a page for each weight interval (usually in 2,000 pound increments) with the appropriate speeds permanently printed on the card'. Turning the booklet to the correct page automatically displays the correct landing speeds, which are then positioned on a prominent place in the cockpit to serve as a memory aid for the approach and landing phase. The speeds from the booklet subsequently serve to set several speed bugs, which can be positioned relative to the airspeed indicator. This is another simple-effective memory aid, which physically stores the speeds until touchdown.

4.2 Results

The following section outlines the application of the steps discussed in section 3, for a case study of a DC-9 cockpit speed setting.

4.2.1 Step 1: Develop a WAD FRAM model

FRAM functions were allocated to exchanges of task-relevant information propagation. We subsequently assigned a JCS agent to each function, responsible for transforming the representation of information from one medium into the next one. This is a bottom-up approach as opposed to assigning top-down functions from a multiple-agent-centered perspective. The model resulted in a total of 107 FRAM functions. The final analysis is supported by the Abstraction/Agency framework that emerges from assigning agents and their roles. Other agents physically located outside of the cockpit, such as flight dispatch or air traffic control (ATC) had to be included in the model, at least for their purpose of feeding weight-and-speed-relevant information to the pilots which were critical inputs for the remainder of the pilots cockpit preparations. Although the traditional model from Hollnagel (2012) assumes that FRAM functions can be started by both human and technical agents, we found this study to be the first to systematically apply complete agent-neutrality. All agents and functions are listed in Table 1. The second layer of the model, i.e. Generalised Function (GF), is sketched in Figure 3. In this figure, as well as Table 1 it can be seen that the Pilot Flying (PF) for example performs two different roles (GF): a) 'managing performance data & aircraft status' and b) 'fly and navigate the aircraft'. Note that the identification of agents and functions is described by step 1 in Figure 2 (see section 3.1, 3.2, 3.3). As our scope is normal work, we did not describe contingencies in detail but created either a background function or a feedback loop, that referred to the point where specific contingencies started and what specifically

Figure 3. FRAM model for the WAD at second level of abstraction.

triggered them. We were mindful that a precise description of a contingency would need an extension of the model, that was not undertaken, but the possibility for this is acknowledged.

The speedcard booklet embodies the pivotal point where the pilots' calculations from the estimated landing weight are turned into the correct speed bug settings for the speed reduction schedule and thus landing. This pivotal moment splits the whole information sequence from one representation into its next form and thereby divides the sequence into two main parts. One part starts with all the functions *upstream* that involve the weights calculations and the second part involves the speed setting *downstream*; in FRAM this is depicted as follows:

The function <Prepare flight plan> from the agent (Flight Dispatch), leads to <Insert initial weights> into the aircraft systems and into the flight plan by the Pilot Not Flying (PNF). This in turn results into <Calculate gross Weight Final> by (PNF). By comparing it to another function <Display gross Weight 'Fuel Panel'>, generated by the agent (Aircraft systems), the (PNF) is able to <Interpret correct Gross Weight>, the function that is later needed to compare the proper function from two sources that may not be in disagreement <Confirm estimated landing weight>. Selecting the correct page of the speedcard booklet transforms the estimated landing weight into speeds. In our FRAM model this function is called <Materialize landing weight calculations> by (PNF), which subsequently leads the pilots to storing the information in an additional durable physical form by the use of two functions: <Set speed bugs PF> and <Set speed bugs PNF>. Later in the model this durable information is cross checked by a reciprocal action from two agents <Cross check [spatial similarity] PF> and <Cross check [spatial similarity] PNF>, an action which by itself is reinforced by a checklist function <Complete descent item landing weight and data from checklist>. These two strings of transformations of information upstream and downstream of the speedcard booklet form the core of this FRAM model. All other functions are either served by it – e.g. configuration changes – or control the joint performance variability by distributed cognition. The PFs roles as having the actual control of the aircraft, are supported by the durably stored outputs of the central weight-speed-string and are intertwined with it by means of distributed cognition through artefacts. Artefacts also act as a medium in spoken-aural challenge-response actions between pilots. A small set of background functions are needed just to close the model. To conclude with a closed model is a FRAM prerequisite.

4.2.2 Step 2: Identify performance variability

In FRAM, the variability of a function is measured by its output variability and can have three different sources, endogenous variability (internally created by the function), exogenous variability (external to the function) and functional upstream-downstream coupling.

The latter is the effect of the variability from the outputs from upstream functions and forms the basis of functional resonance (Hollnagel 2012). Rather than assigning actual or probable variability ranges with the help of our SMEs (e.g., see Patriarca, Di Gravio, and Costantino 2017; Patriarca et al. 2017), we used an explorative approach to define reasons for distributed criticalities in terms of propagation of tasks.

For this study the terms endogenous and exogenous variability are expressed as parameters which fall inside or outside the boundaries of the model. The boundaries coincide with the scope of the study, whereas in reality socio-technical system boundaries extend further.

4.2.2.1 Identify endogenous variability. Endogenous variability could potentially be very high for many functions, for example when pilots set speed bugs incorrectly or even forget to perform certain items. Undesired endogenous variability as the output of a single function can exceed the safety margins, if not corrected in a timely manner.

4.2.2.2 Identify exogenous variability. Exogenous variability is produced by the variability of the work environment (Hollnagel 2012), and in this case study, this could be provoked by stress conditions arising from the aircraft's mechanical contingencies or induced by high traffic flow.

4.2.2.3 Identify functional upstream-downstream coupling. As per the definition of the string of information changes, the core of our case study, is a series of downstream-upstream coupled dependencies. Effective joint control is achieved by other functions' abilities to dampen or correct resonances from individual endogenous functions' variability. Even if undesired variability is introduced by an incorrect pilot input there is a high chance that this is detected by a redundant action. Redundancy between PF and PNF, between pilots and artefacts or between different sources of semantic information offers a high chance to correct previous variability. This was not the case when an incorrect ZFW was forwarded to the pilots by flight dispatch. There are no external agents or aspects that control an incorrect ZFW, once the information has been received in the cockpit. Only the incremental experience from pilots that something is not quite right with the weights in relation to other data could discover a mistake, which is a very random and brittle type of variability control. Examples of how other variabilities can occur but can still be corrected by the system's functional design are discussed in aggregations of all three variabilities in section 4.2.3. The significance of the ZFW propagation criticality was confirmed by the informants from their own experience. Rich narratives about the importance of an artefact so subtle, though implicit as incremental pilot experience revealed a variability that was not accounted for by WAI documentation.

4.2.3 Step 3: Aggregate performance variability

In this section, we explore how variability is aggregated by the model, taking advantage of the functional representation of FRAM, in order to understand and highlight distributed criticalities.

4.2.3.1 Aggregate endogenous variability. Except for the ZFW example, the design of this work system copes well with either correcting or preventing single unwanted internal or endogenous variability. This analysis highlights several ways to reduce unwanted variability. The first is to have a rigid design that reduces variability beforehand. For example, the booklet of speed cards has low internal variability because of its design, its simple use and durable representation. Another method is to correct undesirable endogenous variability by cross-checking two sources of information or even left-and-right symmetries of the same information, as typically found in the cockpit. The corrected output is the joint effect of a variability that can easily be detected by an asymmetry or checked in advance by a third durable medium. Left-right symmetries make cross checking a virtually non-cognitive task. Whether the action is achieved by the artefacts showing an asymmetry or the human agents detecting the asymmetry is only a matter of perspective. Hence, Hutchins makes a significant contribution about the fact that researchers have easier access to the representations available in the cockpit (see section 2.1), than to the representations that result from processes inside individual 'human' actors.

Asymmetries need not be restricted to the result from human actions as in the following flap settings example. Left and right flaps independently move a pointer, although co-located on the same dial as depicted in section 4.2.4. A mechanically stuck flap is likely to occur at one side only and therefore, a split flap position would immediately attract attention by the spatial dissimilarity between left and right pointers. This performance variability of a mechanically stuck flap, emerges in a visual representation at the cockpit level and is transformed into a judgment of spatial juxtaposition, earlier explained by Hutchins

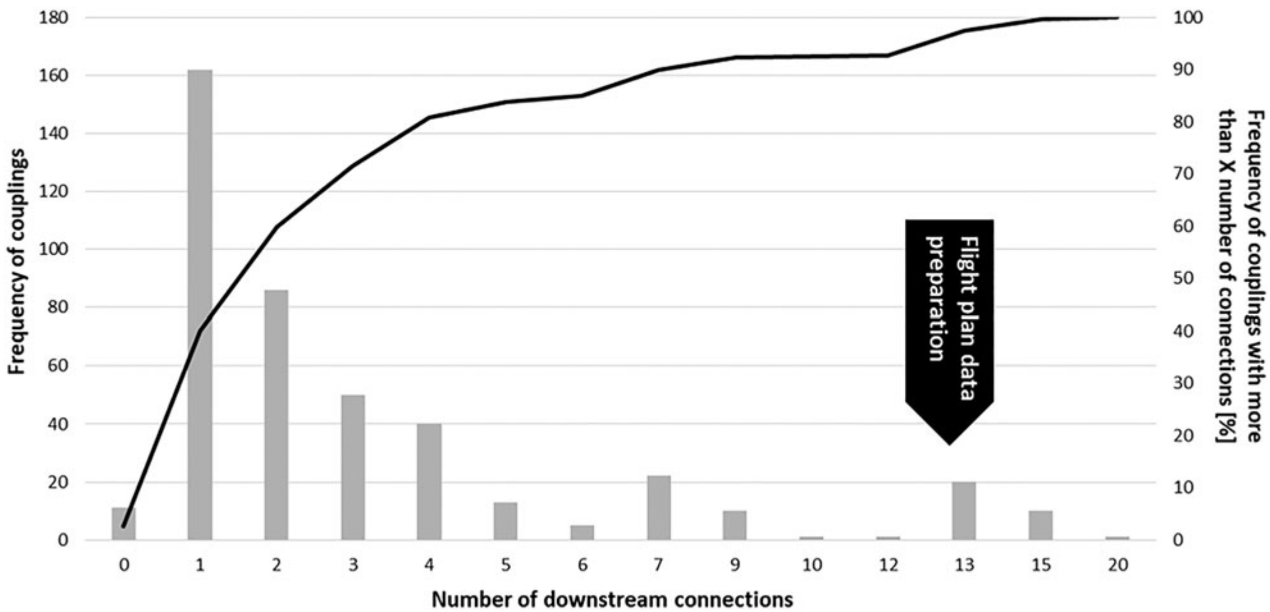

Figure 4. Number of downstream connections (grey histogram) and cumulative distribution of downstream connections (black curve).

(1995a) and Henriqson et al. (2011) in a JCS ethnographic description, but here confirmed by the FRAM language. The propagation of variability in this example is dictated strongly by the fact that the aircraft as an agent has left and right channels of flap actuation, each with their own instrument indication. Although this mechanism supports otherwise scarce human cognitive resources, it can also trick the pilots into the heuristic of believing that flaps are correct when they fail simultaneously, and pointers overlap, although in a wrong position.

4.2.3.2 Aggregate exogenous variability. Exogenous variability in this case has only a minor impact on the system's outcome Even under the normal work analysis from this case study, mechanical or traffic flow contingencies can be dynamically absorbed by flight path management. Critical checklist items can be delayed, but ultimately are coupled as a 'precondition' into accepting a predefined step that precedes the next phase of the aircraft's approach. Even if such a point would be reached before the completion of the cheques, this will initiate an extra function such as <Clearance for additional vectors>, essentially a measure to buy more time. The interviews with our SMEs confirmed that the WAD model 'preconditions' differ from the procedural and often underspecified WAI perspective, but serve as critical points to accept the next phase of the aircraft's approach.

4.2.3.3 Aggregate functional upstream-downstream coupling. In the aggregation phase, we additionally used a semi-quantitative method to identify critical functional couplings. Figure 4 depicts the amount of downstream dependencies for a certain function. Besides the ZFW produced by <Flight plan data preparation>, there are several other functions that are highly connected (e.g. more than 10 downstream dependencies) and therefore were identified as potential candidates for undesirable functional resonances:

- Procedure triggers pilot action (12)
- Artefact matches weight and speeds (13)
- Set speed bugs PF (13)
- Aircraft limitation data memory aid (13)
- PF Manages pitch and power (15)
- Aircraft displays operational data (20)

Eventually, none of the other candidates are particularly critical, as they can be disqualified for several different reasons. Most of them are not specific at all or have no critical influence upon functional resonance without the aggregated output from yet other functions. The function <Set speed bugs> could be critical, but this function is adequately controlled by pilot cross-cheques and additionally triggered by a checklist. <Aircraft limitation data memory aid> refers to a stable performance variability in contrast to the high internal performance variability from the ZFW that varies substantially from flight to flight. Hence, the ZFW from dispatch is the only critical candidate for meaningful coupling variability and can be found at the 97' percentile of the overall distribution (see blue curve Figure 4) where it feeds 13 downstream

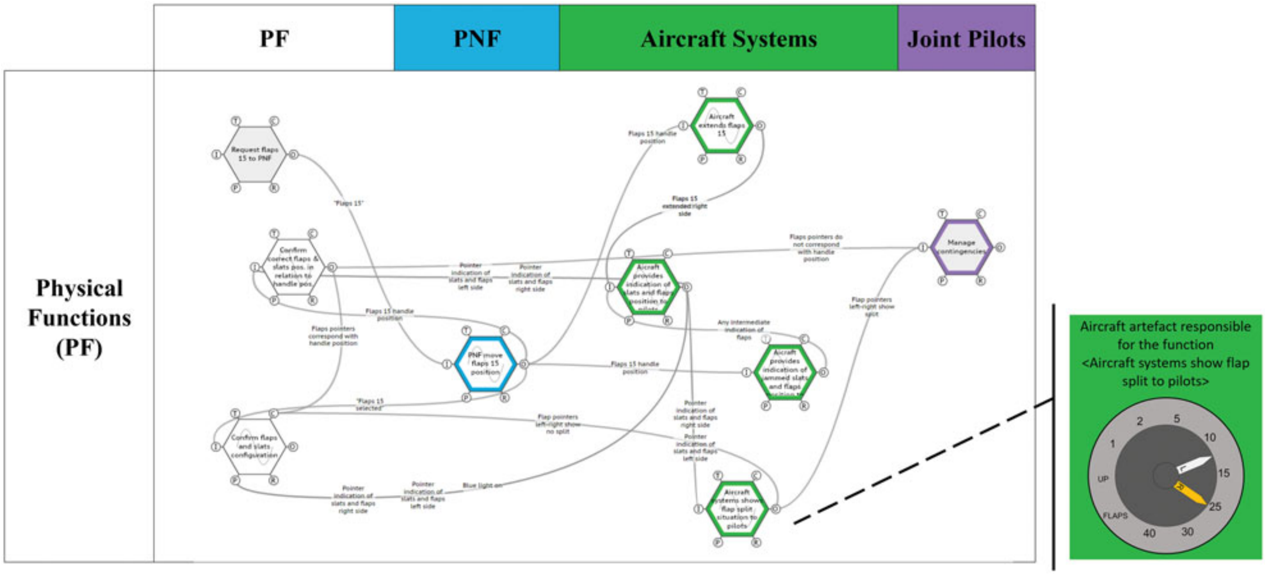

Figure 5. Decomposition of 'Setting flaps 15' into JCS sub-functions by intra-level, inter-agent analysis at Physical Function level. A flap indication instrument with left/right co-located pointers can be found next to figure (The instrument's indication scale is different from the original DC-9 instrument).

functions. Eventually it leads to an incorrect approach and landing speed. Therefore, this function is both quantitatively and qualitatively critical, or can be called super-critical.

It is possible to input an incorrect ZFW so that it spreads throughout the whole system without becoming detected, except by an incident. Henriqson et al. (2011) highlights several incident reports where the ground crew provided incorrect weights to the flight crew and an incident occurred during take-off, which is a positive example of confirmability by triangulation of sources.

4.2.4 Step 4: Manage performance variability

Management of variability to understand complexity in everyday practices begins with understanding the many relationships in complex work analysis from the traditional FRAM model, supported by a meso- or macro-scale analysis from the Abstraction/Agency framework.

4.2.4.1 Manage endogenous variability. Researchers should be mindful that what is defined as a single function in FRAM, is the researcher's choice. Our JCS approach had a very high level of granularity, because it deliberately deconstructed functions into their smallest significant parts and across agents. Instead of traditionally defining a single function <Set flaps 15> that produces a single output 'Flaps are 15', we created a decomposition of 9 functions (see Figure 5) to track all significant action transfers between Pilot Flying, Pilot Not-Flying, the Pilots as a Joint Team and the Aircraft Systems. Managing endogenous variability in our approach consists of understanding what truly is the variability created by a single function, and how this often does not need any explanation of additional constructs from information based human cognitive processes; it simply creates a representation on a joint cognitive level. The left-right asymmetries that emerged between two physical sides are one example how the endogenous variability from sub-functions are only revealed at an appropriate level of granularity, disclosed by using a systematic JCS perspective. The left-right asymmetries are revealed in the bottom green function of Figure 5, which also shows the agent of such function, i.e. a fictious aircraft artefact. Note that the direct reading of the instrument dynamically mimics the left-right flap travel during extension, in addition to its static semantic reading.

Hutchins (1995b) spatial proximity between an air speed indicator and a speed bug in order to maintain speed was a similar mechanism of a direct interpretation of an aircraft's instrument. Paradoxically, understanding holistically how a JCS functions also means understanding its most basic representations, or its deconstruction. The pilots confirmed the significance of this deconstruction for the understanding of their own work and welcomed the understanding of a cockpit as a JCS that consists not only of human agents, but also considers aircraft controls and instruments as agents of their own to systematically describe WAD.

In practice, an example of managing upstream endogenous variability, related to the scenario of this study, can be found in more recent aircraft models equipped with Flight Management System (FMS) where the pilot numerically enters the ZFW as critical flight data. The FMS automatically calculates the GW, comparable to the DC-9's <Display Gross Weight (FMS)>. Current-generation FMS will automatically generate an error message for the ZFW entered by the pilot, when it falls outside one or more reasonable parameters. Many modern aircraft will even automatically match the speed bugs accordingly, which only have to be confirmed by the pilot, an example of downstream endogenous management. In our example this would be the equivalent of choosing the wrong flip page of the speed card booklet, which might only become clear when exceeding the lowest and upper limits of the GW. Modern FMS would consider more than just these ultimate limits to manage the variability of weights and their related bugs.

An example of managing downstream endogenous variability is for example achieved by a Runway Overrun Warning in models like the Airbus 350 and Airbus 380. These aircraft automatically calculate if the runway will be long enough to stop the aircraft, taking into account current wind conditions. Under 500 feet above ground this calculation is based on the actual flown speed, which is targeted by the pilots in relation to the speed bug presets. Although the Runway Overrun Warning is designed for another purpose, it will additionally provide protection for calculation errors or finger trouble errors that result in higher than actual weights.

4.2.4.2 Manage exogenous variability. Exogenous variability influenced only a minority of the functional variability in a normal work analysis, and is dynamically regulated by the flexible, though underspecified timing, from checklist items.

An example of exogenous variability in relation to the model's boundaries can be explained as follows. Typically, European Union airlines take an average of 84 kg per adult passenger for their ZFW calculations. Imagine that a team of Sumo wrestlers boards the aircraft for a championship. The exogenous variability would be substantial, because the ZFW, if not corrected, would be inaccurate for the number of passengers. However, managing such exceptional variability is outside the scope of our model, but could be depicted by an exogenous relation to <Prepare data by flight dispatch>, which leads to <Flight plan preparation> and <Compute cargo and passenger weight>, functions related to the Flight Dispatch department. It would also influence downstream functions for other agents such as the PNF <Insert initial weights>. This variability typically needs to be managed upstream in relation to the models' functions, so flight dispatch can anticipate this unusual influence on the ZFW, from which we know that, if a mistake is introduced, it will propagate through the JCS as shown in section 4.2.3.

A practical example to manage exogenous downstream variability, could exist when, for example, the wind direction changes leading to ATC issuing a last-minute runway change. In this case an exogenous variability would be linked to <React to dynamic traffic situation> and its reverberations. To manage a change in preparing the landing data for a new runway, performed in <Complete descent item landing weight and data from checklist>, pilots could ask delay vectors to ATC to gain time for their landing preparations, including setting the speed bugs. These examples show that although exogenous variability is inherently not covered because it lies outside the scope of the research, the boundaries can be adapted in relation to emerging research questions.

4.2.4.3 Manage functional upstream-downstream coupling. Cross-cheques and durable third source checking dampen undesired downstream dependencies. The Abstraction/Agency framework helps to understand how information passes from one medium to another, as the boundary between medium and agent is abandoned. Note that newer generation of aircraft, although enhanced with technical aids, are still prone to false ZFW interpretations and even introduce new risks from faulty inputs (Henriqson et al. 2011). To actually overcome this problem, there should be an additional possibility of the pilots to check the process involved in creating the ZFW by previous agents. Simply receiving the final outcome is insufficient.

5. Discussion

A transfer of symbolic values among pilots and between pilots and artefacts replaced the procedural processes based on a WAI perspective with a more descriptive WAD perspective. This description of representations and processes, external to the pilots overcomes the problem of inherently reductionist notions from the information processing paradigm (Bergström and Dekker 2014), in which we have no access to the internal representations that underlie human cognition or sense making. In these descriptions of task and information propagation, we are still one step away before reaching a genuine JCS approach, because we have to add how 'pilots create a shared meaning (always partial and thus incomplete) of the working situation' (Henriqson et al. 2011); in other words how pilots gained or lost control of joint control capacities. The cockpit choreography exists by first managing the semantic data before the aircraft's approach, when resources are still readily available. Before the approach reaches its dynamic peak more durable representations are used whereby cognition is distributed over space and time and for which artefacts act as a medium. Spatial proximity or similarity from mirrored or co-located double channel artefacts act as a simple though effective cockpits' cognitive representation created by durable media. Checklist items finally synchronise the pilot's actions in relation to the aircraft continuous progress, which can be very unforgiven if not properly managed. The integral approach of these combined mechanisms constitutes the cockpit choreography.

The critical distribution of functional resonances was studied in a combined qualitative/quantitative approach that pointed to a single conclusion, the uncontrolled introduction and propagation of ZFW from Flight Dispatch, being the one function in which cognitive distribution was surprisingly absent.

This study maps non-linear dependencies, and resonances as tangible results. And by treating humans and machines as equivalent producers of functions, the joint performance of the system can be described as the net result of the resonances between functions at different resolution levels of representation.

Researchers should be mindful to use the appropriate interview questions in the natural language of the operator, and use naturalistic cockpit settings, i.e. 'in the wild' (Hutchins 1995b) with supporting material to uncover the cognitive representations constituted in a cockpit as a whole. This might reveal counter-intuitive or alternative explanations of traditional cognition.

Repeatability in FRAM, but also in other systems thinking models, remains a challenge and is bound to the researcher's epistemological choices. We argue however, that this is true for all safety models, and that the combination of FRAM, Abstraction/Agency framework and a JCS approach provides a reliable research approach.

The biggest limitation to the model is that even with a relatively simple scenario in comparison to modern cockpits, the FRAM model requires a lot of resources from the researcher (i.e. in this case study, it required approximately 150 hours). Modern cockpits, but also non-aviation control rooms, will have even more transformations of information, for example because of higher cognitive participation of systems, or because of more alternative performance variability outcomes. One can think of more automation modes, more system menu options or a greater number of redundant channels, which will inherently lead to more alternative propagations. Therefore, the researcher should limit the scope of the model to the essential questions under investigation, so as to have the possibility of dealing with a manageable model.

The language of transformations of information, translated in a functional model can be used as a generic way to study the joint interactions between human operators and their systems. Work systems can be generically understood by using transformation of information as a token for information exchanges between agents. This modelling method will therefore be generally applicable to a myriad of socio-technical systems where operators interact with other human and technical agents. We believe that representation of information exchange between human and technical agents as a deconstruction of functions in their smallest significant parts – see detailed description in Adriaensen et al. (2017b) – adds to a generic transferability of FRAM model building to other JCS settings. Especially in today's highly coupled and complex flight deck systems, accidents occur because of mode errors and incorrect mode awareness (Sarter 2008), these can be studied as breakdowns of joint cognitive systems.

6. Conclusion

Today's Safety-II principles (Hollnagel 2014) propose that safety should be improved by studying the conditions from normal work, and not just by the investigation of a minority of incidents. However, there are few accepted systemic methods to achieve this goal. By using FRAM together with a JCS Abstraction/Agency framework, one systemic approach is explored.

We revealed how understanding the smallest significant steps is important, while it is also important to maintain a systemic perspective. This approach summarises the need for a deeper understanding of the system's actual functioning. A number of authors have argued that typical human factor labels are not a natural object, but rather a historical object and a cognitive construct (Dekker and Hollnagel 2004; van Winsen 2015), and 'easily get overgeneralized to situations they were never meant to speak about' (Dekker and Woods 2002). We defended ways to understand co-agency under normal conditions and co-agent corrections in reaction to undesired variability. That understanding can be applied to other scenarios, because the language of transformation of information flows as a deconstruction of functions in their smallest significant parts (Adriaensen et al. 2017b) can be generically applied to socio-technical systems' behaviour and adds to a generalizability of building FRAM models to other JCS settings. Turning to managing variability, it should be recognised that today's linear and epidemiologic analyses wherein human shortcomings, or what is perceived as such, are simply replaced by an automated system or mitigated by adding a barrier or redundancy, run a risk of not performing better at all. Nevertheless, the need for intelligent ecological designs is crucial. The FRAM's non-linear understanding of complex systems assisted by JCS inter-agent analyses, affords the means to investigate, express and eventually mitigate CSE issues through systems ergonomics in socio-technical systems in a more effective way.

Notes

1. myFRAM is a software application that operationalises FRAM analyses and can be obtained from http://functionalresonance.com/the%20fram%20model%20visualiser/myfram.html The FRAM Visualiser pre-dates myFRAM and can be found at http://functionalresonance.com/the%20fram%20model%20visualiser/index.html
2. The nomenclature for the two agents on the flight deck used throughout this research is representative of that used within the domain: Pilot Flying (PF) for the handling pilot and Pilot Not Flying (PNF) for the non-handling pilot

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Disclosure statement

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