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Investigating flight crew strategies to cope with unexpected events: a multi-layered extended control model of joint crew-automation activity☆

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ABSTRACT

Although commercial aviation is a highly standardized and ultra-safe industry, there are still times when the flight crew are faced with an unexpected situation, and must respond appropriately. This article studies how to characterize variability in flight crew strategies handling unexpected events, problematic as well as successful. Hollnagel's Extended Control Model (ECOM) is operationalized as an analysis tool for crew-automation Joint Cognitive System (JCS) performance, for simulated B747 and A330 scenarios, as well as more generally for joint activity of crew and automation in airliner cockpits. This development and application of ECOM to two studies in a research flight simulator is described, highlighting crew-automation JCS performance at multiple layers of control. The ECOM analyses are found to be in unison with industry expert ratings, while providing a more nuanced qualitative perspective supporting pattern identification. Various process-tracing visualizations of flight crew strategies in terms of performance at the various ECOM layers illustrate patterns. ECOM and related Contextual Control Model (COCOM) classifications and assessments contribute to the explanation of performance and as a rich qualitative description of desirable performance. Frequent and regular interaction between ECOM layers and tactical/strategic control modes correspond to desirable performance. Recommendations to the aviation industry for preparing pilots better for unexpected events are outlined.

1. Introduction

The current generation of commercial aircraft are designed with highly automated and reliable systems, a development that has many safety benefits. However, as the cockpit operations grow increasingly stable, the amount of variations and disturbances decrease, leaving the crew with little exposure to surprises and unforeseen situations. The effects on the operational work environment are not well understood, since the crew's ability to deal with the unexpected has received less attention in the aviation industry.

Several aviation accidents demonstrate the necessity of crew abilities to cope with situations and surprises beyond the procedures and standard crew training. Examples include, for instance, the ditching of the US Airways Flight 1549 A320 in the Hudson River after an unlucky bird strike (NTSB, 2010) and the successful management of the Qantas Flight 32 A380 engine explosion leading to a series of events and faults (ATSB, 2013). Although the initial threats of these events were anticipated, the full consequences of the failures given the situational circumstances were not, leaving the crew to rely on their individual experience and expertise.

Meantime, the modern role of pilots having to manage automated systems has led to well-documented problems of automation surprise, new attention and knowledge demands, unevenly distributed workload, a degradation of manual skill, and over-trust in automation (Bainbridge, 1983; Sarter et al., 1997; Woods & Hollnagel, 2006). Although known for a long time, these problems seem to persist (Dekker & Woods, 2024; FAA, 2013; Pritchett, 2024; Strauch, 2017; Woods, 2024). Examples include Turkish Airlines Flight 1951 (DSB, 2010), Air France Flight 447 (BEA, 2012), Lion Air Flight 610 (KNKT, 2019), and Ethiopian Airlines Flight 302 (AAIB, 2022).

Operationalizing models conceived by Erik Hollnagel during the last few decades, this article takes a theoretical perspective of Cognitive

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Systems Engineering (Hollnagel & Woods, 2005; Woods & Hollnagel, 2006) and macrocognition (Klein et al., 2003), and relates to Resilience Engineering (Hollnagel et al., 2006; 2011). A Cognitive Systems Engineering and Resilience Engineering approach to complex and dynamic systems, such as commercial aviation, recognizes that operational life contains fluctuations, unexpected events and disturbances that do not always fit the textbook examples and trained scenarios (in aviation documented by, for example, Dekker & Lundström, 2006; Loukopoulos, Dismukes, & Barshi, 2009). To be resilient it is necessary to be well-prepared for anticipated failures, but also more generally to be "prepared to be unprepared" (Pariès, 2011). Research shows that pilots may have difficulty and display great variability between them when abnormal events are presented to them unexpectedly and in other ways than in routine training, suggesting that memorized skills in training do not generalize well to naturalistic surprise settings in the cockpit (Casner et al., 2013). *How to characterize this variability, problematic as well as successful, in terms of crews' strategies in collaboration with cockpit systems,* is an open research question, addressed in this article.

In Cognitive Systems Engineering (CSE), methods that are used to analyze and describe the behaviour of Joint Cognitive Systems (JCS) focus on the characteristics of observable behaviour, or performance (Hollnagel & Woods, 2005). A fundamental part of the CSE approach for studying any particular work practice is that it is studied in its relevant and appropriate context. This allows the influence of factors such as cognitive and situational demands, coordination of work processes and the influence of organizational demands to be part of the analysis (Woods & Hollnagel, 2006). Further, it permits identification of interactions and relationships between people, technology and the work setting. This perspective can be contrasted with more traditional approaches to studying cognition and work where people, technology, and their interfaces are studied separately, each seen as one unit of analysis (Woods & Hollnagel, 2006). In CSE, it is the activities of the Joint Cognitive System (JCS) of people and technology together, the relations between system parts, and the phenomena that emerge as a result of system interactions, that are of main interest (Hollnagel & Woods, 2005). Considering the joint system of both people and technical systems performing functions that can be seen as cognitive (or "macrocognitive") enables an analysis of how they function to perform sensemaking, selecting action, directing attention, handling surprise, etc. (Klein et al., 2003; Hollnagel & Woods 2005). CSE methods analyze the activities of this JCS to describe the patterns and characteristics of observable behaviour (Hollnagel & Woods, 2005). In the cockpit setting, for example, CSE considers both pilots (Pilot Flying (PF) and Pilot Monitoring (PM)) along with the aircraft automation and technical systems, as a JCS.

Central for the ability to control a process and successfully adapt is sensemaking. The concept of sensemaking targets both the retrospective and prospective oriented aspects of making sense, that is, sensemaking aims to frame both the processes of how we make sense of events after they have occurred and, simultaneously, how we anticipate future events (Klein, Snowden & Pin, 2010; Klein, Wiggins, & Dominguez, 2010; Rankin, Woltjer, & Field, 2015; Weick, Sutcliffe, & Obstfeld, 2005).

The Contextual Control Model (COCOM) is at the core of CSE (Hollnagel & Woods, 2005). It contains a control loop, based on Neisser's (1976) perceptual cycle, a cyclical model showing the relation of human perception and action and is. Fig. 1 is an adaptation of COCOM to the crew-aircraft context and demonstrates the cyclical process of how the current Understanding of the situation leads to crew Actions on the Process to be controlled (light blue), i.e. flying the aircraft. Actions together with External events and Disturbances produce Events in the process, and Feedback. Events and Feedback modify the Understanding of the situation, and the loop continues. The COCOM modelling also includes criteria to determine the degree of control (see Section 2 on Method).

In the Extended Control Model (ECOM) (Fig. 2), cognition is again described as control (Hollnagel & Woods, 2005). The ECOM comprises four parallel control loops, each similar to the COCOM cyclical model (Fig. 1), which makes ECOM a multi-layered model of cognition and human action. This functional model can be used to examine the distribution of tasks and roles across the different people and technology performing various functions, e.g., crew members and aircraft systems controlling the aircraft. Several layers of control loops are applied to describe how anticipatory (feedforward) and reactive (feedback) control are performed simultaneously by the system. As a situation unfolds the distribution of tasks and roles may change and the focus and attention of the crew may shift, demonstrating how the crew-aircraft system adjusts to respond to an event. This includes, for example, how different levels of automation affect the team play between the pilots and automation, how overarching goals provide targets for layers below and how

Fig. 1. The cyclical model of human action and perception, conceptually applied to the crew-automation JCS (adapted from Hollnagel & Woods, 2005).

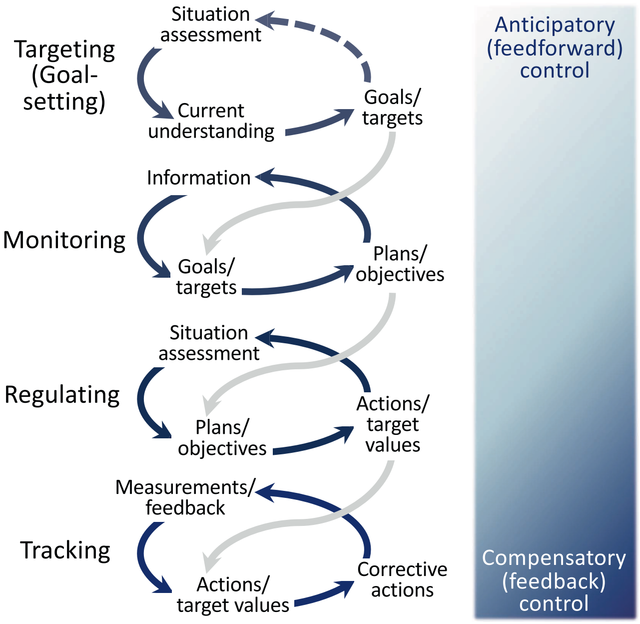

Fig. 2. The Extended Control Model (ECOM) (adapted from Hollnagel & Woods, 2005).

feedback from the lower layers provide input to revision of goals and targets.

This functional account of the joint system recognizes that a system's performance takes place simultaneously on multiple layers of control (Fig. 2). The four layers of interacting control loops in the ECOM thus describe how a JCS set targets (e.g., "heading for destination"), monitors (e.g., "monitor flight path"), regulates (e.g., "reduce speed ahead") and tracks performance (e.g., "adjust speed"). The goals set at the targeting layer provide inputs and targets for the monitoring, regulating and tracking layers and reversely the tracking layer provides input to the revision of goals and targets. Simultaneous anticipatory (feedforward) and reactive (feedback) control is shaped by the contextual conditions and system constraints.

Hollnagel's perspective on Cognitive Systems Engineering follows Ulric Neisser's (1976) arguments for a more realistic study of cognition in people's ordinary environment (out of the laboratory) as part of purposeful activity, warnings of not overcommitting to the information processing model of cognition, and recommendations of paying attention to fine-grained details and structure of the real world and complexity of cognitive skills. Hollnagel's approach to CSE (Hollnagel & Woods, 2005), including the COCOM and ECOM models, is meant as an alternative to the study of information processing as part of individual cognition in laboratory settings, which its typical foci on mental constructs, still very much present today in fields such as Cognitive Engineering and Human Factors (Engineering). Typical of Hollnagel's style of aiming to overcome limitations of current models in Human Factors and System Safety with practicable concepts and methods, during the 1990s and early 2000s he proposed CSE models such as COCOM and ECOM to provide new concepts and associated methods and vocabulary. CSE deliberately uses another unit of analysis (the JCS, defined by its functions) and another focus (anti-entropic ends, control). It recommends to study JCSs in the wild (with "cognition" distributed across multiple actors and artifacts, similar to Hutchins, 1995), appreciating their context and complexity. These concepts were proposed as a stark contrast to (still much-used) information processing models, providing analytical vocabulary and tools as alternatives to these models' associated terms, such as the popular information processing constructs of mental workload and situation awareness.

Hollnagel's work, after publishing the CSE books (Hollnagel & Woods, 2005; Woods & Hollnagel, 2006) transitioned into Resilience Engineering (again with Woods, e.g., Hollnagel, Woods, & Leveson, 2006) and later the Functional Resonance Analysis Method (FRAM; Hollnagel, 2012) and Safety-II (Hollnagel, 2018), all resulting in considerable academic and industrial uptake (Herrera et al., 2024; Patriarca et al., 2020). The philosophy and teachings of CSE still resonate well with these later developments, for example through their common functional rather than structural approach, focus on coping with complexity and understanding performance variability, and aim towards systems or systemic thinking. COCOM and ECOM are central to his take on CSE, parsed as "(CS)E, meaning the engineering of (cognitive systems), or the design and building of joint (cognitive) systems" which Hollnagel (2022a) recently described as "still very much relevant". Meanwhile, he has not been disinclined to critique his own earlier work, and for example has called his Cognitive Reliability and Error Analysis Method "obsolete" (Hollnagel, 2022b), moving on to other methods for functional performance variability and resilience modelling, particularly FRAM (Hollnagel, 2012) and Systemic Potentials Management (Hollnagel et al., 2021).

Illustrating Hollnagel's perspective of multi-layered control, COCOM and ECOM have been applied in the (empirical) analysis of human–machine systems in aviation (e.g., Blom et al., 2001; Dijkstra, 2006; Feigh, 2008, 2011; Feigh & Pritchett, 2010; Feigh et al., 2007; Inoue et al., 2012; Kim et al., 2026; Kontogiannis, 2011; Kontogiannis & Malakis, 2012, 2013; Langan-Fox et al., 2009; Lundberg & Johansson, 2021; Rankin, Woltjer, & Field, 2015; Verma et al., 2003), and other domains (e.g., Berglund, 2012; Engström and Hollnagel, 2007; Gauthereau and Hollnagel, 2005; Hybinette et al., 2023; Kannally et al., 2025; Kontogiannis, 2010, 2012; Leecaster et al., 2017; Palmqvist et al., 2012; Porathe, 2018; Praetorius and Hollnagel, 2014; Renner and Johansson, 2006; Son et al., 2018; Stanton et al., 2001; Tran et al., 2007; Van Westrenen and Praetorius, 2014; Windridge et al., 2012; Worm, 1998; Banbury et al., 2008; Hollnagel et al., 2003; Taylor, 2002; Weir et al., 2012). This article contributes to the expanding body of literature on the practical application of Hollnagel's macrocognitive functional Joint Cognitive System control theory as expressed through COCOM and ECOM.

1.1. *Research questions*

The following operationally driven research question has guided the experimental design and analysis work: *How do crews search for information, manage uncertainties, prioritize and make trade-offs, assess risks, consider options and anticipate future events?* Framing this research question from a Cognitive Systems Engineering perspective, this results in the following two methodological research questions: *How can patterns in joint cognitive systems' control strategies be identified?* and *Which joint cognitive systems control strategy patterns can be identified in order to understand and explain performance?* Considering the nature of this Special Issue of Safety Science on the work of Erik Hollnagel, the emphasis of this paper is on the second and third research questions, showing how the answers to these latter questions can be used as a methodological support to answer operational questions such as the first research question. For a more elaborate discussion of the operational aspects of the analysis, focusing on the first research question, see publications elsewhere (Field et al., 2016; Niedermeier et al., 2018).

2. Method

This section describes the experimental design and the modelling methodology used.

2.1. *Experimental design*

There were different experimental scenarios in the two experiments. Both scenarios were developed by operational experts within the consortium including representatives from aircraft manufacturers, operators and training organisations.

The experiments were conducted with actual airline crews in a realistic setting, at the NLR Generic Research Aircraft Cockpit Environment (GRACE) full-flight research simulator facility set up for simulating the Boeing 747–400 (Experiment 1) and the Airbus A330 (Experiment 2). While recruited from multiple airlines, crews consisted as far as possible of a captain and a first officer (F/O) from the same airline. Data from 12 crews (Experiment 1) and 10 crews (Experiment 2) was used for COCOM/ECOM modelling.

2.1.1. *Scenarios*

Experimental scenarios were developed by operational experts including representatives from aircraft manufacturers, operators and training organisations. Experimental scenario 1 (Field et al., 2016) focused on the final descent and approach phase to an airfield, after a long-haul flight. Three key events in the scenario formed the unexpected events that were being studied. The first occurred during the final approach to the runway – an increase and shift in the wind, destabilising the approach path leading to a go-around. An additional loss of visibility at the decision height would force a go-around if necessary. During the go-around, the second event occurred, which was a subtle failure of the autopilot heading control that would necessitate a reversion to manual control to regain control of the aircraft heading. The third event was a birdstrike during the go-around climb-out that caused a failure of engine 1, and damage to engines 3 and 4. The damaged engines would surge and stall until thrust was reduced on those engines, at which point the aircraft could be stabilized. The crews were free to decide the appropriate response to the failures, and to decide on the course of action, for example returning to the airfield for a landing, or stabilising the aircraft and diagnosing the problems before landing.

Experimental scenario 2 (Niedermeier et al., 2018) started at Amsterdam Schiphol Airport. The scenario was set up with the aircraft being positioned at the departure runway's holding point when the crew entered the cockpit. After the departure briefing the crew departed and followed along the pre-programmed FMS track southward, which passes just east of a squall line heading toward Amsterdam. Approximately nine minutes after departure the oil temperature of engine 2 caused an ECAM advisory (flashing oil temperature indication). If the crew did not perform any countermeasures within two minutes of time, the still increasing oil temperature caused an "Engine 2 Oil Hi Temp" ECAM warning that demands for an engine 2 shut down. Shortly after the warning two additional failures are introduced by a lightning strike: a "Thrust Lever 1 Fault" and a failure that causes the autothrust to work unreliably. Note that the autothrust failure is not documented in the aircraft manuals. It was artificially created by the scenario designers. The consequence of this failure was that the autothrust could only be activated in certain modes requiring constant thrust, e.g. open climb or open descent. In that case speed control is performed by the pitch control. As soon as the autothrust was set to speed mode (i.e. thrust controlling speed) the system was deactivated or could not be engaged at all. This complex failure further generated uncertainty on the system state of the A/THR. The weather situation including the thunderstorm movement and the wind situation at the different alternate airports was defined such that the weather was favourable at the alternate airports in comparison to the departure airport. However, the departure airport was favourable from an operational point of view. Due to the approaching front the airport was expected to close in short time. In addition to that strong crosswinds were expected for the landing on the departure airport. This weather situation thus created ambiguity in the decision-making process of the crew concerning the selection of an appropriate landing airport.

The main events in the experimental scenarios of the two experiments are summarized below (for further description and rationale behind the scenarios see other publications (Field et al., 2016; Niedermeier et al., 2018)).

Experiment 1:

- Increase in wind destabilising the approach (in combination with bad visibility this forced all crews into a go-around).
- Autopilot failure preventing the autopilot from following the commanded heading.
- Birdstrike causing a failure of engine 1, and engines 3 and 4 to start surging and stalling.

Experiment 2:

- Oil temperature of engine 2 causes an ECAM advisory (blinking oil temperature indication), which leads to the warning 'ENG2 OIL HI TEMP'.
- The airplane is hit by a lightning strike, which leads to a disengaged autothrust and the ECAM warning 'THRUST LOCK' and 'ENG1 THR LEVER FAULT'.
- Bad weather approaching Amsterdam airport.

2.1.2. Data collection

For both experiments, the research simulator was set up to record data for the analysis of the flight crew's actions, decisions and behaviour, including simulator log data, audio and video recordings. Informed consent was obtained. The crew's communication and actions were captured during the analysis by transcribing the video and audio recordings. The data used in the COCOM/ECOM analysis presented in this paper consisted primarily of the observation log, video data (of the cockpit, flight crew and displays), and audio recordings from the flight deck. At the end of the experimental scenario, the flight crew were debriefed by the project researchers. Debriefing data is not in focus here. Performance of the crews was rated by three industry experts, constituting Desired Flight Crew Performance (DFCP) ratings that reflected the percentage of a set of expected or desirable actions and decisions carried out (Field et al., 2016; Niedermeier et al., 2018).

2.2. Modelling methodology

The analysis methodology is illustrated in Fig. 3, describing the methodology for both experiments. The following sections go through the specifics related to both experiments and the incremental modelling approach with the ECOM modelling efforts after experiment 2 building upon the results of experiment 1. Both modelling efforts employ several new process tracing (see Woods, 1993) visualizations for ECOM.

2.2.1. Modelling related to experiment 1

The COCOM classification scheme aims to describe the degree of control that the crew-automation Joint Cognitive System has in a specific time period of performance. A classification of the control mode (strategic, tactical, opportunistic, scrambled) per flight phase was made mostly using the literature definitions as proposed by Hollnagel & Woods (2005), see Table 1. This classification is a subjective assessment based on several parameters: Number of goals, subjectively available time, evaluation of outcome, and selection of action. The Number of goals was not explicitly used as primary indicator of control mode because of difficulties of operationalizing the concept. Subjectively available time, evaluation of outcome, and selection of action were assessed by two of the raters[1] that also performed the later ECOM classification.

The ECOM (Hollnagel & Woods, 2005) is a model to describe multiple layers of performance of the joint crew-aircraft system. This functional model can be used to examine the distribution of tasks and roles across the different crew members and aircraft systems. Several layers of control loops are applied to describe how anticipatory (feedforward) and reactive (feedback) control are performed simultaneously by the system. As a situation unfolds the distribution of tasks and roles may change and the focus and attention of the crew may shift, demonstrating how the crew-aircraft system adjusts to respond to an event. As such, an ECOM analysis is in a first instance a means to describe crew performance, with the ability to depict activities in context, on multiple timescales. This includes, for example, how different levels of automation affect the team play between the pilots and automation, how overarching goals provide targets for layers below and how feedback from the lower layers provide input to revision of goals and targets. Once this has been done the researcher will look for patterns in the data (bottom-up) and use research questions as a guide to search for patterns (top-down).

To operationalize the ECOM the layers have been defined to fit the context of the crew-automation JCS. These models according to the CSE view of data analysis need an application and anchoring into an operational field of practice in order to be applied to analyze observational data. This is why considerable knowledge of operations and aircraft systems is necessary to produce a useful analysis.

Each of the four ECOM layers is described and defined through the experimental data and context. Assigning the observations to the different layers was done through an iterative process of classifying video observations and interview data based on the theoretical descriptions of the ECOM model (Hollnagel & Woods, 2005). The dataset

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[1] One rater (JF) had combined aeronautical engineering and human factors background, and one rater (RW) had human factors and CSE background.

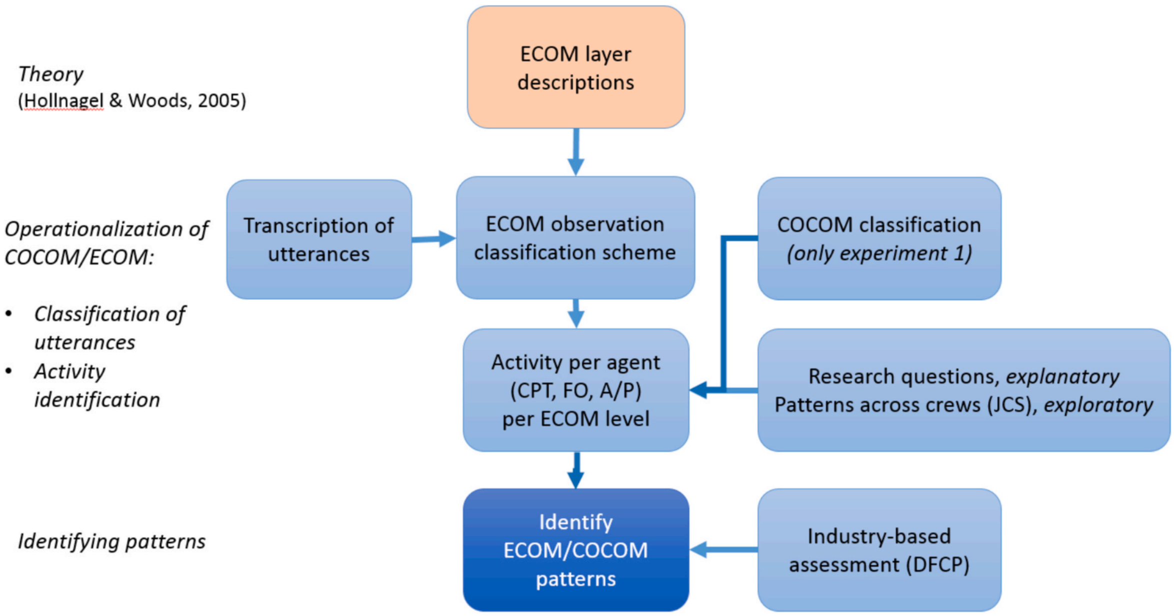

Fig. 3. Analysis process for video observations using the COCOM/ECOM.

Table 1
Summary of the COCOM control mode classification scheme (Hollnagel & Woods, 2005).

Control mode	Number of goals	Subjectively available time	Evaluation of outcome	Selection of action
Strategic	Several	Abundant	Elaborate	Based on models/ predictions
Tactical	Several (limited)	Adequate	Detailed	Based on plans/ experience
Opportunistic	One or two (competing)	Just adequate	Concrete	Based on habits/ association
Scrambled	One	Inadequate	Rudimentary	Random

from two crews were used to develop the classification scheme using three independent raters.[2] Then the classification scheme was documented and extended iteratively reaching full inter-rater consensus while being applied to the remaining datasets. Although this development was laborious and challenging in the beginning, the classification scheme soon converged and gained full consensus, after having experimented with three-layer and five-layer operationalizations.[3] After a four-layer consensus was established, the remainder of the observational data was categorized in a straightforward way following standards for qualitative content analysis. This resulted in a corroborated operationalization of ECOM through the transition from raw observation data into ECOM activity types.

Patterns were identified, in terms of which activities were undertaken by the crew-automation system at each ECOM layer, for a selection of flight phases/segments and crews. The flight phases/segments analyzed may be described by the headings of:

1. Manual reversion (after HDG failure)
2. Engine management (after bird strike)
3. Trajectory management second approach (after Go-Around) to landing

In order to link the COCOM/ECOM descriptions to the operational evaluation of performance as done by industry partners, the relationship between COCOM/ECOM results and DFCP ratings was investigated. To describe which DFCP items were associated to each of the flight segments, see Table 2.

2.2.2. Modelling related to experiment 2

The ECOM operationalization and classification scheme was adapted to fit the scenario in used in experiment 2. The video observations were transcribed using the program ELAN. The use of ELAN as a transcription tool was motivated by its ability to show exact length of the utterances by all agents, as well as their temporal placement in relation to each other on different ECOM layers.

As in the first experiment, the transcribed material was classified into

Table 2
DFCP items of the scenario of experiment 1.

Flight phase/segment	DFCP item
Manual reversion (after HDG failure)	Verbalize HDG fail Immediate manual reversion
Engine management (after bird strike)	MI for surge stall (pull back TLs on affected engine) MI for engine failure on 1 No cycling of fuel on 3 and 4 Verbalize surge/stall Run ENG FAIL NNC Run SURGE NNC Operate engines below surge
Trajectory management second approach (after Go-Around) to landing	Review of aircraft/system status, options Get info from ATC on WX, RWY availability Assessment of RWY for 2nd landing based on weather, etc. No landing with tailwind Controllability review Discuss energy mgmt implications Briefing, G/A no option Execute landing checklist

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[2] One rater (JF) had combined aeronautical engineering and human factors background, and two raters (AR, RW) had human factors and CSE background.

[3] Note that: “The assumption of multiple layers of activity is crucial for the modelling approach, but the specific number of layers or loops is not.” (Hollnagel & Woods, 2005, p. 149).

ECOM layers based on the ECOM classification scheme. For experiment two the activities were grouped by time and ECOM layer. Each activity was then abstracted into one of twelve abstract activities (Fig. 4, left side) and colour coded. The colour coding offered a way of nuancing and better understanding what activities the crews were performing on each ECOM layer, the excerpt in Fig. 4 (right side) shows what the analysis looked like.

The focus of the subsequent pattern analysis was on differences in performance between crews grouped by their landing location and their DFCP ratings. Pattern identification was done using the abstracted colour activities together with the ECOM classification and visualized in scatter plots. Based on the identified patterns further analysis was done on aspects of the data by dividing planning activities into long term and short term planning, thus creating an ECOM model with a subdivided Planning layer. Groups were identified and the performance for each group was compared within and between the crews, using the research questions to guide the research.

3. Results

3.1. *First experiment (B747) and modelling*

This section describes the modelling results of the first experiment.

3.1.1. *COCOM and ECOM operationalization*

The COCOM and ECOM classification schemes were operationalized for the cockpit environment of the B747 experiment. As a preliminary answer to the question "How can patterns in joint cognitive systems control strategies be identified?", the ECOM modelling results of this operationalization are presented in Table 3.

After the ECOM classification was applied to all 12 crews of the B747 experiment, the following question may be addressed:

Returning to the research question "Which joint cognitive systems control strategy patterns can be identified in order to understand and explain performance?", the three previously identified flight phases will be addressed, with a focus on the phases of engine management (after the bird strike) and trajectory management after the go-around, i.e. the second approach to the landing. First, however, some of the identified patterns of manual reversion after the HDG failure will be discussed.

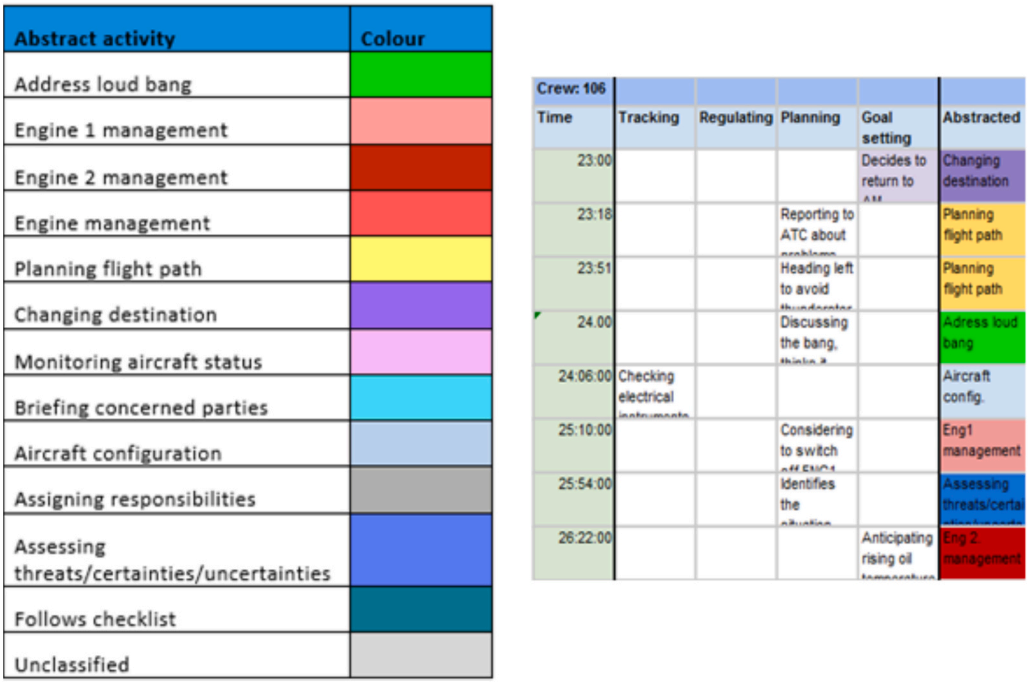
3.1.2. *Manual reversion (after HDG failure)*

To describe the variability of the crews' handling of the manual reversion after the HDG failure, three crews' ECOM patterns were examined. The number of events in a relatively quickly discovered HDG failure, by all crews except the three that already had switched off the autopilot and thereby did not encounter the problem in the same way, did not necessitate a full ECOM analysis for all 12 crews. Crew 6 had already switched the autopilot off and thus did not experience the HDG failure, but later during the second approach decided to switch the autopilot back on in order to reduce workload (monitoring/planning), and then execute the A/P engagement on the regulating layer, and evaluating its performance (regulating). This pattern of action thus followed through the layers and included an evaluation. Crews 10 and 12 disengaged the autopilot after detecting the autopilot was not working. They subsequently did not reconsider the re-engagement of the autopilot, likely because they experienced the HDG failure. This pattern could be summarized as basic evaluation, without re-evaluation. Thus, although the automation failure turned out not to be a major issue in the scenario for the crews, the ECOM layers could be used to illustrate differences in using the A/P between crews.

3.1.3. *Engine management (after bird strike)*

For practical reasons of availability of analysis time, and to focus on the broadest variability of performance among crews, 9 crews with scores around the lower (5) and higher (4) ends of DFCP performance were selected for a description of the ECOM control strategy pattern and COCOM control mode for the activity of engine management, i.e. handling engine performance after the bird strike. Examples of the ECOM classification and patterns for the activity of engine management are presented in Fig. 5 and Fig. 6.

Table 4 summarizes the findings. The ECOM pattern was titled to summarize the pattern that was found on the activities within and between the control layers of Targeting, Monitoring (planning), Regulating, and Tracking. Then subjectively available time, kind of evaluation of information, and what was used for the basis of decision and action were assessed, from which a COCOM control mode was



Abstract activity	Colour
Address loud bang	🟩
Engine 1 management	🟥
Engine 2 management	🟥
Engine management	🟥
Planning flight path	🟨
Changing destination	🟪
Monitoring aircraft status	🟪
Briefing concerned parties	🟦
Aircraft configuration	🟦
Assigning responsibilities	⬛
Assessing threats/certainties/uncertainties	🟦
Follows checklist	🟦
Unclassified	⬜

Crew: 106					
Time	Tracking	Regulating	Planning	Goal setting	Abstracted
23:00				Decides to return to	Changing destination
23:18			Reporting to ATC about		Planning flight path
23:51			Heading left to avoid		Planning flight path
24.00			Discussing the bang,		Adress loud bang
24:06:00	Checking electrical				Aircraft config.
25:10:00			Considering to switch		Eng1 management
25:54:00			Identifies the		Assessing threats/certai
26:22:00				Anticipating rising oil	Eng 2 management

Fig. 4. Colour coding of abstracted activities (left), example of representation in ECOM analysis (right).

Table 3
Summary of the ECOM control layer classification scheme (operationalized for Experiment 1 on the B747-400, based on Hollnagel & Woods, 2005).

ECOM layer	Abstract activities	Example activities in the Man4Gen airline cockpit context
Targeting	Setting and resetting high-level goals of what may happen in the future: • Anticipatory situation assessment • Considering need to reset goals and target • Prioritizing between goals • Anticipating risks /consequences of actions	• Considering feasibility of potential G/A and its consequences • Considering alternative RWY, alternative APT • Anticipating consequences of following or changing FPL • Anticipating consequences of actual or expected weather conditions • Anticipating consequences of early turn to final approach • Anticipating consequences of APP and G/A with degraded engine performance
Monitoring /Planning	Plan monitoring and planning actions, where is the A/C going to be and how it is going to get there: • (Re-) plan and prioritize tasks • (Re-) plan trajectory • Monitoring and information push/pull situation, conditions, systems, for planning purposes (future-oriented) • Identify /decide process phase	• Monitor flight path /discuss flight route • Information retrieval on aircraft status and environmental conditions (e.g., fuel, weather, LOC availability, RWY in sight, WX Brief (ACARS or ATIS), AIP, ATC, look out, need for G/A based on visibility and decision height) • (Re-)planning of flight path (use understanding of aircraft configuration according to priority) • Read MAP from AIP to establish common ground, go through the route in FMC and arrival plates • Function allocation and responsibilities (to crew or A/P) for execution of functions • Identify /decide flight phase status inclusive checklist and briefing and memory items "triggers" • Decision not to do checklist, continue approach decision, inform ATC of G/A, requesting of vectors from ATC, discussion of cabin/passengers' needs • ATC landing and SID/STAR clearances
Regulating	Carrying out the tasks as part of the plan that has been put together in the monitoring layers: • Allocation of Tracking tasks to operators /systems • Setting values according to plan • Monitoring if values are according to plan (here and now – includes environmental conditions, systems) • Planning of Tracking tasks	• Identifying current values (e.g., call out values) • Set/monitor (crew) values according to plan from monitoring or feedback from tracking (for A/P HDG SEL, ALT HLD, SPD, ATHR [+disconnect /override], speed marks, speed vs. flaps setting, auto-brakes, ILS frequency, ATC frequency, minimums, QNH, landing data, ATC clearances, LOC, G/S, speed marks, etc.) • Planning of braking after landing, flaps, gear • Carrying out procedures (e.g., need to take manual control, need to cut-off and recycle engines, need to run engine at less power, need to G/A based on tracking parameters, etc.) • ATC clearance (here and now, e.g., turn to HDG, climb to FL, etc.) • Prepare /inform cabin crew /passengers
Tracking	Actions that have a direct impact on the A/C control surfaces, direct effect on the A/C behaviour: • Operate controls • Monitor controls • Monitor sensor values	• A/P actions through Flight Control System • Monitoring of current HDG, ALT, SPD, positive rate, engine performance, sensor values • Manual operation of thrust, stick, gear, flaps, perception of yaw movements

generated.

The Desirable Flight Crew Performance (DFCP) expert ratings (elaborated elsewhere; (Field et al., 2016)) were related to the ECOM and COCOM results in the sensemaking analysis. This was done to relate the descriptive analysis of ECOM, and the assessment of COCOM, to an industry assessment of performance. The purpose of the DFCPs was to rate each crew (PF/PM combined) against the key actions that were expected by the aviation industry expert observers for specific moments in the scenario. The DFCP ratings were an account of the decisions made and actions taken as either carried out or not carried out.

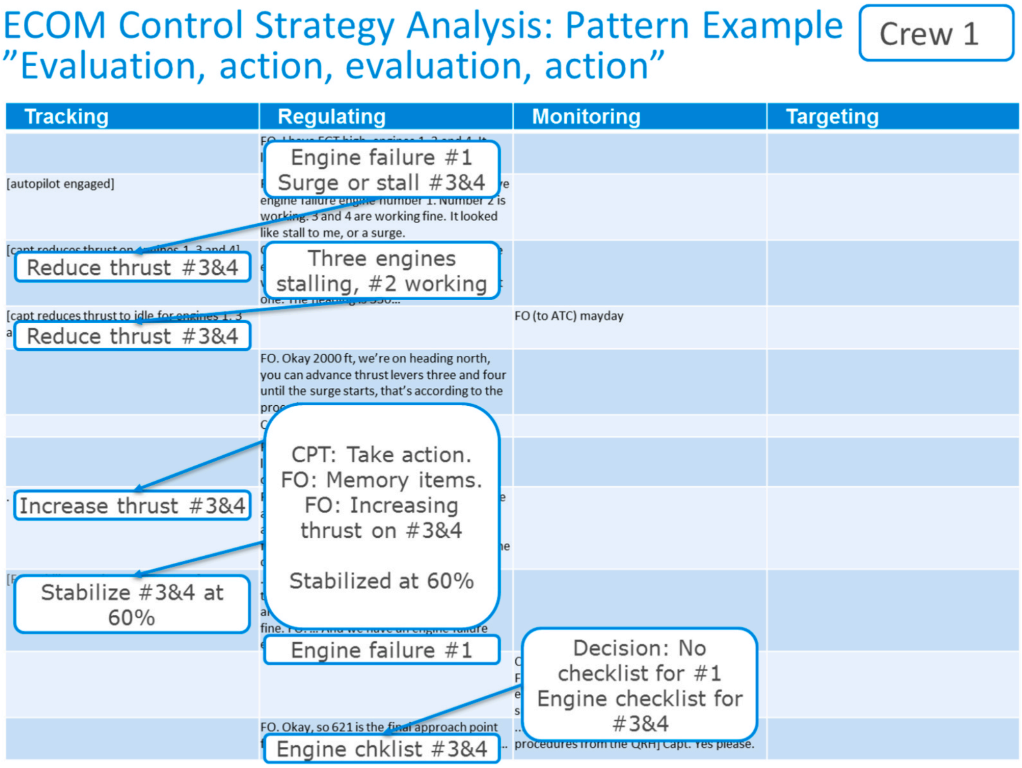
The table below includes the percentage of the score that the industry raters assigned to each crew out of the maximum number of DFCP events carried out of 7 for this activity. Note that %-DFCP from a COCOM/ECOM perspective should be seen as a best-available approximate indication of performance because the equal value of 1 point per DFCP item and the linear addition of DFCPs to a performance score is a simplification to enable at least some kind of quantitative comparison beyond the qualitative ECOM descriptions.

3.1.4. *Trajectory management second approach (after G/A) to landing*

The same 9 crews with scores around the lower (5) and higher (4) end of DFCP performance were selected for a description of the ECOM control strategy pattern and COCOM control mode for the activity of performing the second approach, i.e. flying the approach to landing after the go-around. Note that this activity is to a large extent concurrent to the activity of engine management as described above. Thus, prioritization that the crews did between the two activities were included in the analysis of control modes. Table 5 summarizes the findings in a similar way as for engine management above.

3.1.5. *Analysis*

In general, higher performance (according to industry experts' DFCP definition and scoring) was associated to patterns where there is more interaction between the ECOM layers of Targeting, Monitoring, Regulating, and Tracking. Generally, most activities are triggered as part of procedures or checklists at the monitoring/planning layer and then subsequently discussed between the crew at the regulating layer, decisions for actions are made, and finally implemented at the regulating or tracking layers. In turn, tracking and regulating activities by crew members and indicators from the aircraft systems are observed and discussed, tracking indicators at the higher regulating layer, and regulating indicators discussed at the monitoring/planning layer. If, on the basis of feedback and evaluation, minor adjustments need to be made to the execution of the plan, this is done at the regulating layer. If the trajectory needs to be changed to reach the same higher level goal of the flight, these "flight plan" changes are discussed and decided at the monitoring layer. When necessary and with a certain regularity, at the targeting layer higher-level goals and prioritization between these goals

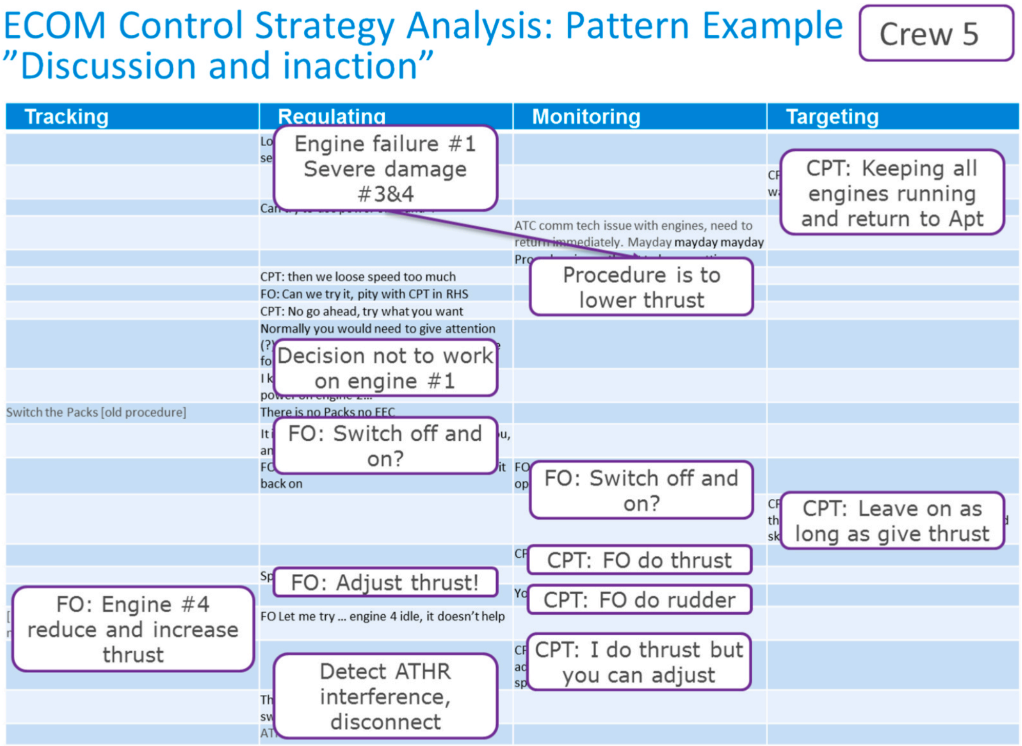


ECOM Control Strategy Analysis: Pattern Example
”Evaluation, action, evaluation, action”

Crew 1

Tracking	Regulating	Monitoring	Targeting
[autopilot engaged]	engine failure engine number 1. Number 2 is working. 3 and 4 are working fine. It looked like stall to me, or a surge.		
		FO (to ATC) mayday	
	FO. Okay 2000 ft, we’re on heading north, you can advance thrust levers three and four until the surge starts, that’s according to the		
	FO. Okay, so 621 is the final approach point	procedures from the QRH] Capt. Yes please.	

Fig. 5. Example of ECOM pattern labelled “Evaluation, action, evaluation, action”.



ECOM Control Strategy Analysis: Pattern Example
”Discussion and inaction”

Crew 5

Tracking	Regulating	Monitoring	Targeting
		ATC comm tech issue with engines, need to return immediately. Mayday **mayday mayday**	
	CPT: then we loose speed too much		
	FO: Can we try it, pity with CPT in RHS		
	CPT: No go ahead, try what you want		
	Normally you would need to give attention		
Switch the Packs [old procedure]	There is no Packs no EEC		
	back on		
	FO Let me try … engine 4 idle, it doesn’t help		

Fig. 6. Example of ECOM pattern labelled “Discussion and inaction”.

is done, consequences anticipated, and the target (e.g., runway, alternate airport) is discussed and decided upon.

Thus, if there is a regular and frequent interaction between the activities at the various layers of control, performance tends to be better.

Crews with less desirable performance tend to have difficulties in the follow-through and follow-up between the interactions between the ECOM layers. This can mean that decisions at the monitoring/planning layers do not result in regulating and tracking actions, and vice versa that observations and actions at the tracking and regulating layers are not followed-up on the regulating and monitoring/planning layers. If

Table 4
Engine management and DFCP rating.

Engine Management of crew #	ECOM pattern	Subjectively available time	Kind of evaluation	Base for decision and action	COCOM control mode	DFCP %
1	Evaluation, action, evaluation, action	Created adequate time	Detailed evaluation	Plans and experience	Tactical	57
2	Identify, discussion, action	Adequate time	Concrete evaluation	Based on association	Opportunistic (tactical)	29
4	Evaluate, prioritizing actions	Just adequate initially /later inadequate for actions (short turn)	Concrete evaluation, then rudimentary	Decisions based on association	Opportunistic > scrambled	43
5	Discussion and inaction	Inadequate time for decisions and actions, after discussion of evaluation	Concrete evaluation w.r.t. engine evaluation (much discussion without status evaluation /decision)	Decisions and actions random	Scrambled /opportu–nistic	29
6	Evaluation, action, evaluation, action, recap	Adequate time created to manage the situation and decisions	Elaborate evaluation of status and leading to actions and recap	Actions and decisions based on predictions and experience /plans	Tactical /strategic	71
8	Quick actions, little discussion, evaluation of status, priority	Just adequate time – inadequate (limit their goals)	Concrete evaluation of actions /status	Actions from association	Opportunistic	57
10	Identify, act, evaluate	Create adequate /abundant time	Evaluation elaborate, with recap after decision	Evaluation and actions are planned, based on expectations /predictions	Strategic (tactical)	57
11	Unsynchronized discussion analysis and action	Just adequate time	Loosely organized	Scanty planning	Opportunistic	29
12	Immediate action, less evaluation	Just adequate to manage engines on downwind, then early turn to base so that there is inadequate time (self-created situation)	Rudimentary evaluation when there is time, thereafter little at all	Actions based on association or random, when time is inadequate	(Opportu–nistic) –> scrambled	14

Table 5
Second approach and DFCP rating.

Second APP of crew #	ECOM pattern	Subjective–ly available time	Kind of evaluation	Base for decision and action	COCOM control mode	DFCP %
1	Identify problem, request assistance, assess and follow through	Create adequate time	Evaluation of decisions /actions is detailed	Based on plans and experience /advice	Tactical	63
2	Set high level goal and get assistance, unclear plans followed and executed, mismatch in interaction with automation, repeated recaps	(Just) adequate time available	Detailed evaluation	Actions based on habits /association	Opportu–nistic (tactical)	63
4	No discussion, limited evaluation, aim to land	Create just adequate time	Rudimentary evaluation of situation /decisions	Based on association, experience	Opportu–nistic (scram–bled)	0
5	Identify & assess, consider alternatives in plan and execution, prioritize flying	"Create" just adequate time	Detailed evaluation	Actions based on plans /experience	Tactical (opportu–nistic)	38
6	Evaluation, double check, actions follow through across levels	Abundant time, taking time,	Elaborate evaluation	Actions based on plans /experience	Strategic /tactical	75
8	Discussion of options, evaluation, priority > decision and actions to save time	Just adequate time, limit goals to time available	Detailed evaluation of options, decisions	Actions based on planning and experience	Tactical (opportu–nistic)	50
10	Prioritize evaluation and problem solving, actions, risk assessment and evaluation. Take time.	Create abundant time to run procedures, evaluation,	Evaluation of decisions is elaborate	Decisions and actions based on plans and experience	Strategic > tactical	75
11	React and extend planning horizon, buy time	Available time: Adequate > Abundant	Detailed evaluation of outcome	Based on prediction and experience	Tactical > Strategic	75
12	Actions without prior evaluation, information not discussed	Subjective time inadequate (just adequate)	Rudimentary evaluation	Actions based on habits /association	Scram–bled (opportu–nistic)	13

monitoring/planning decisions and observations are not regularly or when necessary lifted to the targeting layer, important considerations regarding choice of runway, and consideration of alternate, and other trade-offs and prioritization of goals may be missed. This in turn may lead to lower-layer activities that could be better adjusted to situational circumstances if they would be evaluated and reoriented by higher-layer activities, but instead continue to execute plans that are not well-adjusted to circumstances.

The activities at the various layers between which interaction occurs are presented in Table 6 with a high level description.

An analysis was performed between the match between COCOM control mode classifications (distinguishing between Scrambled, Opportunistic, Tactical, and Strategic modes, and nuances in between these modes) and the DFCP ratings. In order to do this a numerical value was assigned to each control mode, from 1 assigned to Scrambled to 4 assigned to Strategic, mapping these control modes on values on a highly simplified linear interval scale of control modes. Nuances between control modes were translated, e.g. tactical with aspects of opportunistic, noted as tactical (opportunistic), translated to 2,75, and opportunistic-scrambled or opportunistic going to scrambled translated

Table 6
High level description of crew activities.

ECOM layer	Activities
Targeting	Setting and resetting high-level goals of what may happen in the future: • Anticipatory situation assessment • Considering need to reset goals and target • Prioritizing between goals • Anticipating risks /consequences of actions
Monitoring (planning)	Plan monitoring and planning actions, where is the A/C going to be and how it is going to get there: • (Re-) plan and prioritize tasks • (Re-) plan trajectory • Monitoring and information push/pull situation, conditions, systems, for planning purposes (future-oriented) • Identify /decide process phase
Regulating	Carrying out the tasks as part of the plan that has been put together in the monitoring layers: • Allocation of Tracking tasks to operators /systems • Setting values according to plan • Monitoring if values are according to plan (here and now – includes environmental conditions, systems) • Planning of Tracking tasks
Tracking	Actions that have a direct impact on the A/C control surfaces, direct effect on the A/C behaviour: • Operate controls • Monitor controls • Monitor sensor values

to 1,5, etc. It should be noted that this was done in order to assess a high-level rough correspondence between CSE-based and industry-assessment-based accounts of performance.

However, while interpreting these results, careful consideration should be taken for these assumptions and simplifications of both of these performance assessments while interpreting these results. Fig. 7 should be seen purely as a visualization. No further statistical analysis is presented, as COCOM and DFCP ratings cannot be considered comparable interval scale measures. For this reason some outliers would be expected, explanations may be traced to the COCOM and ECOM descriptions and DFCP scores above. For engine management these are, e.g.: lower than expected/average control mode for crew 8 relative to DFCP score, higher control mode for crew 2. For the second approach these are, e.g.: lower than expected/average control mode for crew 2 relative to DFCP score, higher control mode for crews 4 and 5.

The results in Fig. 7 show that higher control modes correspond to higher DFCP scores. Generally crews manage to get to tactical and strategic (higher) control modes by creating more available time, discussing and evaluating indicators and events in a detailed or elaborate manner, and taking plans, experience, models and predictions into account. These aspects, as summarized by the control modes, correspond well with the DFCP scores, i.e., the desired actions and considerations as based on the industry assessment of actions by the flight crews. We therefore interpret the ECOM and COCOM classifications and assessments to contribute to the explanation of performance and as a qualitative description of desirable performance, with a frequent and regular interaction between ECOM layers and performance with a tactical/strategic control mode corresponding to desirable performance.

3.2. *Second experiment (A330) and modelling*

This section describes the modelling results of the first experiment.

3.2.1. *ECOM re-operationalization*

While operationalizing the ECOM for Experiment 2 in the A330 setup (see Table 7), also the names of the ECOM layers were updated. To make the name of the layers more in line with operational aviation terminology, *Targeting* as originally in ECOM (Hollnagel & Woods, 2005) was revised to *Goal Setting*, and *Monitoring* as originally to *Planning* (as did for example Van Westrenen & Praetorius, 2014, in the maritime traffic domain). Moreover, *Regulating* was clarified by adding the term *Task Execution*, and *Tracking* was clarified with *Action Execution*. Also, the interaction between the layers was articulated explicitly.

The ECOM analysis showed that there is a big variation in the performance of the crews. This includes the time they took to carry out the scenario, the decision process used and the actions taken as shown in Table 8. It also shows an overview of the distribution of activities on different layers, as well as the relation between layers (to avoid issues regarding the different time span of scenarios).

The tendency identified in this analysis is that with a higher DFCP (Niedermeier et al., 2018) score crews spend less time/effort regulating and more goal setting in relation to the amount of planning activities compared to the crews with a lower DFCP score.

Example ECOM layer activity distribution scatterplots for all crews can be found in Fig. 8.

Returning to the research question "Which joint cognitive systems control strategy patterns can be identified in order to understand and explain performance?", as an initial step to identify the control strategies used by the crews in their decision on where to land the first five minutes after the decision to cancel flight and the last five minutes before the decision of where to land were analyzed. The motivation behind this timeframe for analysis was to capture the performance when crews are in a similar situational position in their flight and thus comparable (e.g.,

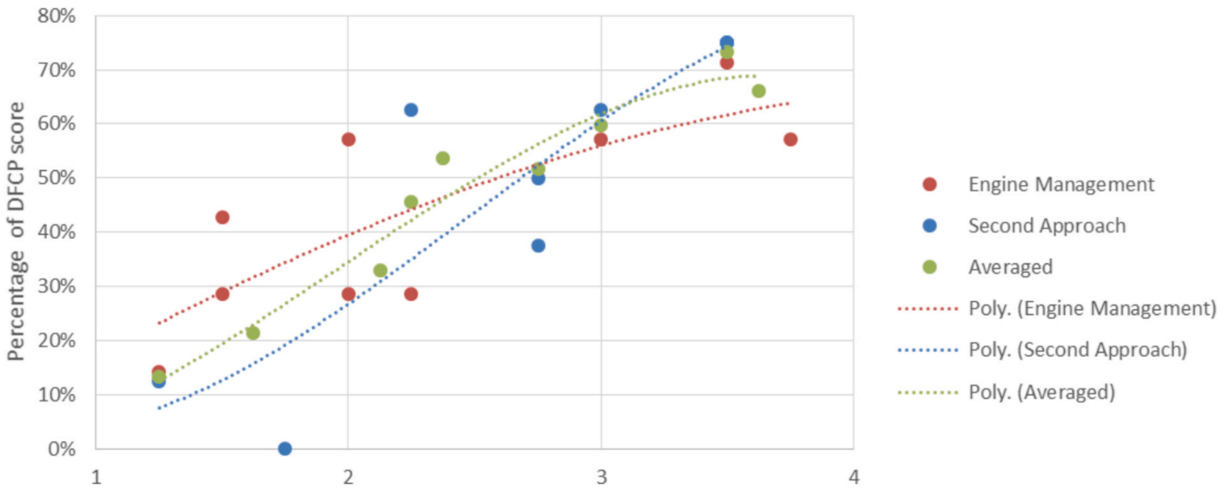


Fig. 7. Visual representation of COCOM control modes and DFCP scores for nine B747 crews, for Engine Management and Second Approach, and averaged, including 3rd order polynomial trends. COCOM control mode 1 represents Scrambled, 2 Opportunistic, 3 Tactical, and 4 Strategic.

Table 7
Summary of the ECOM control layer classification scheme (updates for Experiment 2, A330).

Activity layer	ECOM layer abstract activities	Example activities from experiment 2
Goal Setting	Goal (re-)setting, prioritization, and trade-offs	Choosing destination for landing, deciding which engine to troubleshoot
	Monitoring goal achievement	Check location relative to destination on radar
	Anticipating consequences of alternative plans	Deciding which altitude to go to in the event of a G/A
	Anticipating situations and environmental conditions	Anticipating consequences of actual or expected weather conditions
	From Planning: Plan achievement towards goals	Planning for eventual G/A
	To Planning: Goals to plan for	
Planning	Planning and prioritizing of tasks to achieve goals	Informs co-pilot of current location (for planning purposes), about weather situation
	Monitoring plan achievement	Switching RT responsibility
	(Re-) plan high-level progress (trajectory)	Informs ATC/flight technical about engine problem, plans ATC landing (and takeoff) and SID/STAR clearance
	Information exchange for planning purposes (future-oriented), about the situation, environmental conditions, systems, etc.	
	Allocation of tasks to agents (to systems or crew members) as part of plans	Decides to turn IDG off
	From Regulating: Task achievement as part of plans	Report plans for future actions to ATC, request weather information at from specific airport
	To Regulating: Tasks to execute as part of plans	Planning of waypoints, Discuss flight path, Make alternative plans, Ask ATC for vectors in particular direction, Confirming weather report from ATC
Regulating	Execute tasks as planned	Orders co-pilot to execute actions (switch on seat belt sign)
(Task Execution)	Allocation of action execution to agents (to crew members or A/P systems)	Monitoring ECAM page, status page
	Setting target values for tracking/action execution	Restart engine, initiate landing
	Scheduling and monitoring of action execution	Instruct crew member to lower landing gear
	From Tracking: Action completion as part of task	Follow procedures and checklists
	To Tracking: Target values for crew/systems to act on	Contact purser with information, Address passengers with information, Following new clearance from ATC, Thrust lever to FLEX, Pull STD, QNH, Troubleshooting engines, Set AP, Switches to thrust descent, Acknowledge master caution light
Tracking (Action Execution)	Execute actions as part of task that have direct impact on process to be controlled (A/C flight path, flight envelope)	Monitors engine oil temperature
	Operate controls	Manual operation of thrust, stick, gear, flaps, perception of yaw movements
	Monitor controls	Monitoring of HDG, ALT, speed, positive rate, engine performance, sensor values
	Monitor sensor values	Turn off IDG, APU GEN on, GEN on/off, ENG on/off

all crews had just experienced a lightning strike, or each crew was making the final decision on where to land). A challenge in comparing the crews has been that they take very different durations of time in performing the different activities.

3.2.2. Long term/short term planning strategy patterns

The ECOM analysis showed that the difference in activities of the crews were mainly in the actions and planning activities (Table 9). In this context "actions" refer to any activity where the crew performs an activity at the Regulating layer or the Tracking layer that serves to achieve a direct change in the situation, for example lowering the landing gear or pulling the speed brakes. A "planning" activity is an activity performed at the Planning layer or the Goal-setting layer where the crew actively creates a plan to do something, be it something simple as planning to increase speed or something more abstract such as formulating a long term plan. The analysis shows that the patterns of actions and planning activities differed between crews that landed at Amsterdam and the crews that landed at Brussels. The crews that landed in Amsterdam spent a considerably larger portion of their time on actions than the Brussels crews. An analysis of the activity types at the different layers offers an understanding of this result. It was noted that there was a difference in the anticipatory and compensatory planning activities carried out by the crews. In the next phase of the analysis these planning activities (short- and long-term planning) was thus analyzed in more detail.

To investigate the crew's decision making process of where to land following the main events in the scenario the anticipatory items in the industry based assessment (DFCP) (Niedermeier et al., 2018) related to this decision were identified (Table 10). The results show two groups, those with scores of 4 and above (green) and those with scores 3 and below (red). All crews in the higher rating group landed at Brussels (BRU) and all crews with a lower rating score landed at Amsterdam (AMS). An exception is crew 104 who made two landing attempts at Amsterdam before deciding to go to Brussels.

The anticipatory part of the ECOM analysis was subsequently grouped either as short term planning or long term planning. In Table 11, a distinction between the two levels of planning is made and examples of both types is provided.

The distribution of the long and short term planning activities were plotted in graphs, as exemplified in Fig. 9. The analysis focuses on two types of planning: engine management and navigation. The red dots denote engine management and the green dots denote navigation. Layer 5 denotes short-term planning and 6 denotes long-term planning.

The graphs provide an overview of the distribution of the planning activities, taking into account both the level of planning as well as the type of activity the planning concerns. However, no clear pattern could be found, indicating that a deeper pattern analysis of the decision process was required. Four main strategy patterns for how the crews reframe the situation and reach their decision on where to land were identified.

The crews were grouped after their anticipation-related industry expert based assessment score (DFCP). Four different strategy patterns were identified as part of this analysis, two strategy patterns for the lower-scoring group and two patterns for the higher-scoring group. The differences in the patterns were greatest between the crews that landed at Brussels and the crews that landed in Amsterdam. The two sets of strategies used by the Brussels crews (highest-scoring two strategies, Fig. 10) show a similar pattern of early-on information gathering and assessment that affect the flight long-term. Some differences can be found between the crews in how the interactions between short and long term play out. The crews that landed at Amsterdam (lowest-scoring two strategies, Fig. 11) show two different patterns. The first is the crews that "get stuck" on short-term planning (e.g., managing the engines, descent path and near-by weather). Discussion of landing options is only performed once the crews are close to Amsterdam, at which point the unfavourable weather conditions create an additional surprise. The

Table 8
ECOM layer distribution.

Crew	Total activities	Tracking	Regulating	Planning	Goal setting	Goal setting ratio to planning	Regulating ratio to planning
101	46	7	14	20	5	0.25	0.7
102	76	5	28	36	7	0.2	0.78
103	106	25	31	47	3	0.06	0.66
104	200	18	79	93	10	0.1	0.85
106	28	4	5	14	5	0.3	0.36
107	31	4	5	20	2	0.1	0.25
108	63	6	18	33	6	0.2	0.54
109	48	8	17	19	5	0.2	0.89
110	42	6	12	19	5	0.25	0.63

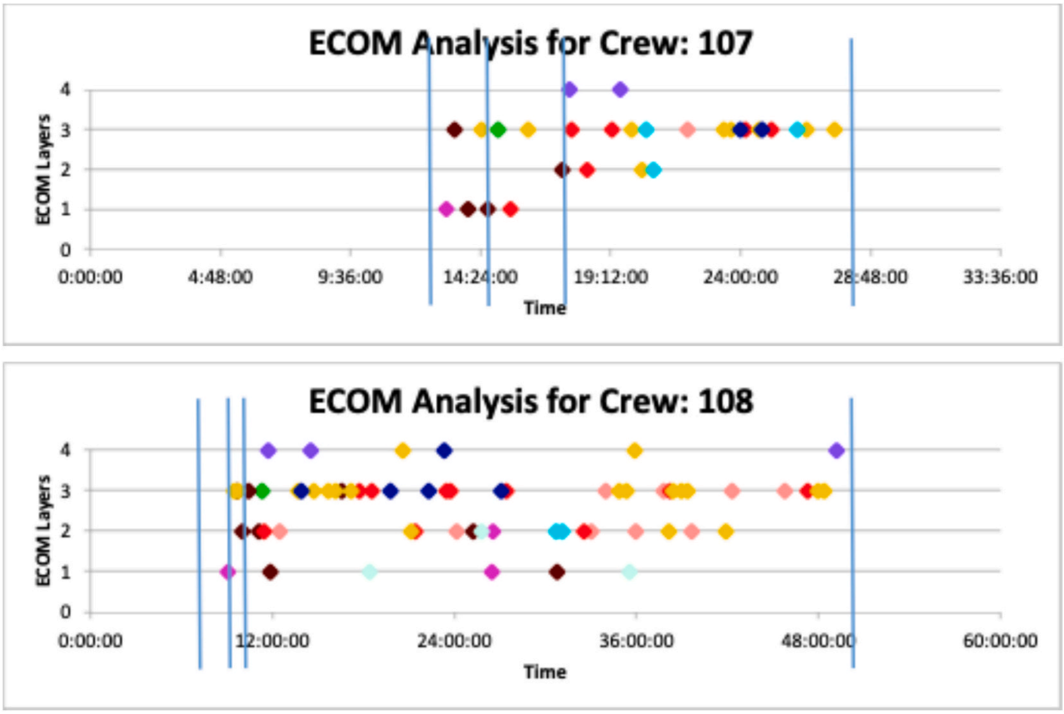


Fig. 8. Example scatterplots for two crews.

Table 9
Summary of actions and planning activities the first 5 min after decision to cancel flight, 5 min before final decision of where to land and the amount of planning activities between the two 5 min analyses.

Part of scenario	Final destination	Total activities	% actions	% planning
5 min after decision to cancel flight	Amsterdam	27	48.1	51.8
	Brussels	17	23.5	76.4
5 min before decision where to land	Amsterdam	47	38.3	61.7
	Brussels	26	11.5	88.5
Amount of planning between 5 min analyses	Amsterdam	90		
	Brussels	23		

second pattern of strategies include the group of crews that make a rapid decision on limited information (e.g. only information regarding weather in Amsterdam) without considering other options.

3.2.3. *Analysis*

Inter-group strategy patterns appear to be more similar than cross-group strategy patterns. The strategy patterns of the higher scoring group took considerable less time to gather information, evaluate options and make a decision. Lower scoring crews had a tendency of “getting stuck” in short-term planning and lacked information that could potentially generate more options. The ability to quickly re-frame and get back up to the higher layers and see the “bigger picture” at an early stage following the unexpected appears to be a determining factor for crews that get a higher score on the anticipatory items of the industry assessment. The results from experiment 1 showed that interaction between the ECOM layers is critical for successful operations, that is, to not get stuck either at higher layers (not taking action) or lower layers (unable to re-form plans and consider options ahead). This pattern was identified also in experiment 2, where “getting stuck” on short-term planning resulted in less informed decisions and generated additional surprises.

4. Conclusions and discussion

Results from the ECOM layers analysis offer unique insight into the multiple processes going on simultaneously in the cockpit. By capturing these processes it is possible to analyze and identify how time, uncertainty, risks and contextual factors affect the actions taken and the decisions made by the crew. One of the greatest challenges of applying the ECOM for this type of analysis was the great diversity in the performance of the crews (likely a reflection of the complexities, uncertainty, and difficulty built into the scenarios). Even though all crews are faced with the same scenario and operate under the same conditions, the length, process, and final outcome of their flight varied considerably. For this

Table 10
Anticipation-related DFCP items.

Anticipation-related DFCP items	101	102	103	104	106	107	108	109	110
Collect information of weather at nearby fields	Yes	Yes	No	No	Yes	No	Yes	Yes	No
Discuss weather situation before diversion decision.	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes
Do not land at AMS	Yes	Yes	No	Yes	Yes	No	Yes	No	No
Continue using ENG1 for approach/landing	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Check impact of failures on landing performance	Yes	No	No	No	Yes	No	Yes	No	No
Discuss G/A performance risk	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No
Total number of Yes	5	4	2	3	6	2	6	3	2
% Yes	83	67	33	50	100	33	100	50	33

Table 11
Definition of long/short term planning.

Type of planning	Definition	Example
Short term	Planning concerned with activities that are situated in the present or the near future.	Requesting vectors towards landmark, planning continued descent.
Long term	Planning concerned with activities that are situated in a, given the context, more distant future.	Deciding at which airport to land, requesting weather conditions at an airport.

reason the ECOM-based analysis method was refined repeatedly to answer the research questions. Besides adjusting the ECOM cockpit operationalization, re-classifying the activities at the planning and goal setting layer as either short- or long-term planning is an example of this refinement that helped produce more meaningful results than the original layers' classification.

The ECOM classification schemes were operationalized for the scenarios and cockpit environment of the B747 and A330. The ECOM operationalizations for the scenarios and aircraft types of the experiments have been generalized into crew-automation goals, plans, tasks, and actions. ECOM layers have been renamed and short- and long-term planning activities of the renamed Planning and Goal-setting top layers have been distinguished, extending the published domain-independent ECOM (Hollnagel & Woods, 2005). These aviation operationalizations are major results of the study as this is (to our knowledge) the first empirical application of ECOM to a cockpit environment at this scale.

Both experiments' modelling efforts feature several new process-tracing (Woods, 1993) visualizations for ECOM. The use of ELAN as an analysis tool in the second experiment was considered useful as it allowed the transcription and categorization of the content into different ECOM layers in the same program. The subsequent coding of the activities of the ECOM into abstract categories with different colours developed during the second experiment were also considered valuable as they allowed for a deeper analysis of the content of each layer, resulting in a strategy pattern analysis.

The COCOM control modes and ECOM layers and long term/short term planning analysis associate well with (anticipation-related) DFCP scores as defined by aviation experts. One of the benefits of contrasting the DFCP scores with the ECOM analysis is that ECOM is a descriptive method that provides a more nuanced description of crew performance, compared to quantitative expert judgement scores such as DFCP. DFCP deals in Boolean questions, whether a crew performed a certain action or not, to which the CSE arguments against the use of human error counting (Dekker, 2003, 2007) may very well be applicable: Using DFCPs only, performance is rated in terms of counting the occurrence of actions against predefined expectations, a Boolean comparison to Work-as-Imagined rather than an explanation of Work-as-Done (Hollnagel, 2018).

Instead, ECOM enables a focus on broader patterns of actions over longer time periods in context, explaining how actions (whether marked as DFCP items or not) came about in relation to higher control layers of regulating, planning, and goal-setting, as well as the consequences of these actions. The ECOM thus offers a deeper and more nuanced understanding of crew-automation performance. The result that the COCOM/ECOM and DFCP analyses have been performed independently and found to be congruent has here been used as a means to show the validity of COCOM and ECOM, in lack of other performance metrics. COCOM and ECOM have here been shown to provide more nuanced evaluations than (and answers to explanatory follow-up questions beyond) merely checking whether expected human actions have been

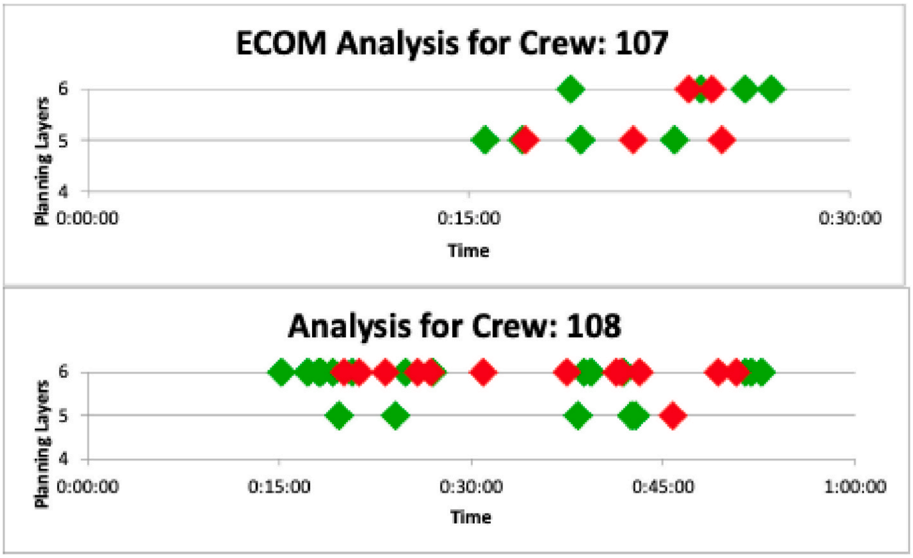
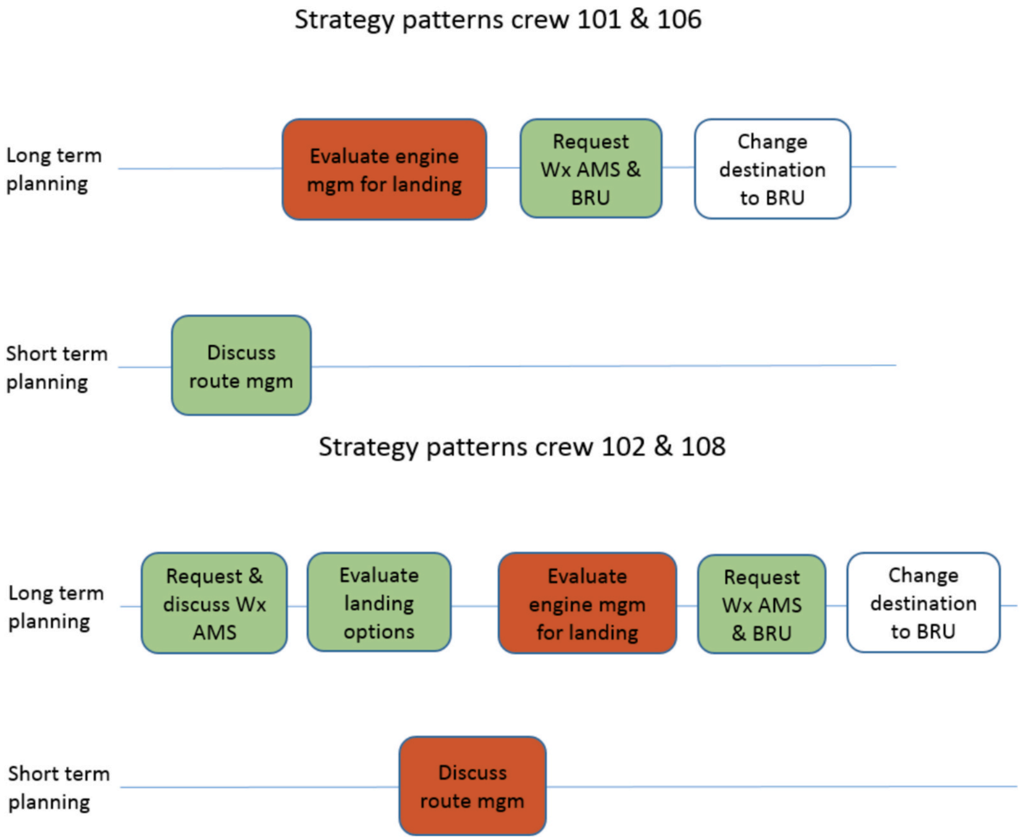
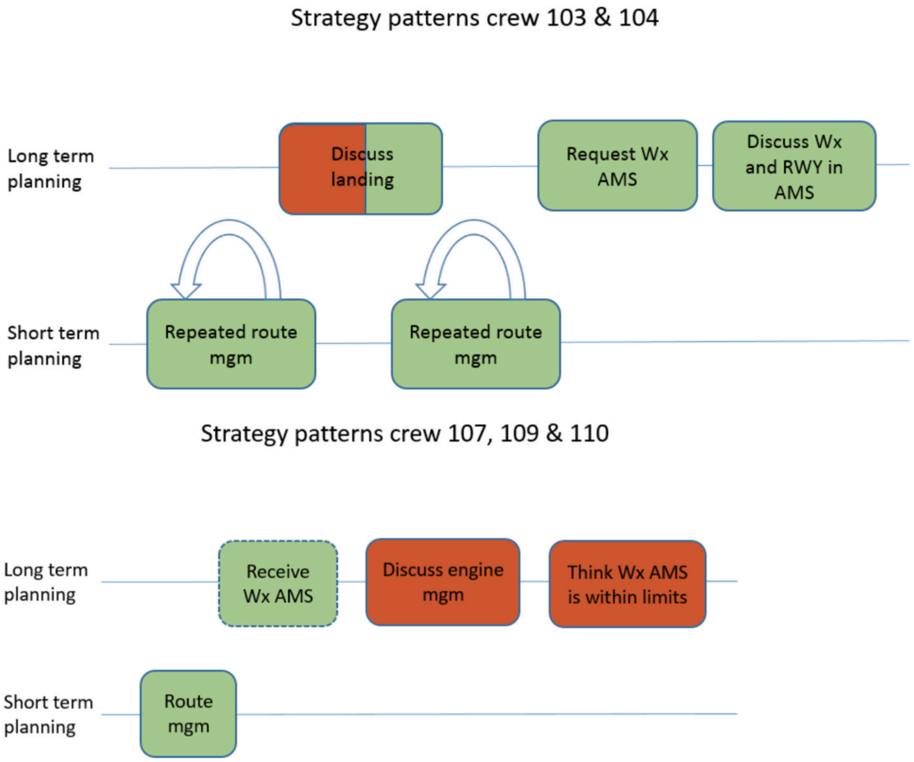


Fig. 9. Example scatterplots for Long/short term planning for crew 107 and 108.


Strategy patterns crew 101 & 106

Strategy patterns crew 102 & 108

Fig. 10. Strategy patterns crew 101, 102, 106, and 108, with higher DFCP scores.


Strategy patterns crew 103 & 104

Strategy patterns crew 107, 109 & 110

Fig. 11. Strategy patterns crew 103, 104, 107, 109, and 110, with lower DFCP scores.

performed or not. For evaluation metrics in future research, but also operational assessment of crew performance, we therefore recommend the further exploration of the use of multi-layer control loop pattern identification and analysis, over time, in context. As the breadth of published COCOM and ECOM studies to date indicates, this recommendation should indeed extend to *evaluations* of socio-technical system/team performance that from a CSE perspective always would strongly benefit from rich *descriptions and explanations* of performance variability in safety–critical domains, generally. Practically, this entails a similar process presented in this study, including adaptation of the COCOM and ECOM to specific operational contexts, including adjusting the vocabulary, number of layers, and fine-grained description of activities at each layer of the ECOM, to particular domains.

Patterns emerging from the ECOM analysis show that struggling crews tend to have difficulties in the follow-through and follow-up between the interactions between the ECOM layers. Continuous interactions between the ECOM layers appears to be critical for successful operations, that is, to not get stuck either at higher layers (not taking action) and lower layers (unable to re-form plans and consider options ahead). This can mean that decisions at the monitoring/planning layer do not result in regulating and tracking actions, and vice versa that observations and actions at the tracking and regulating layers are not followed-up on the regulating and monitoring/planning layers. If monitoring/planning decisions and observations are not regularly performed, or, when necessary, not lifted to the goal-setting layer, important considerations regarding choice of runway, and consideration of alternates, and other trade-offs and prioritization of goals may be missed. This in turn may lead to lower-layer activities that could be better adjusted to the circumstances if they would be evaluated and reoriented by higher-layer activities, instead of being continued, which leads to the execution of plans that are not well-adjusted to circumstances. For example, in experiment 2 several crews “got stuck” on short-term planning following the lightning strike, due to uncertainties regarding the incident, as well as deteriorating weather near-by. The time spent on short-term planning resulted in less informed decisions and further generated additional surprises such as bad weather at the destination airport. The ability to quickly re-frame and get back up to the higher layers and see the “bigger picture” at an early stage following the unexpected appears to be a determining factor for crews. This resonates well with what Woods & Branlat (2011) have called “getting stuck in outdated behaviours”, a concept to which ECOM here provides analytical support, also illustrating a link between ECOM and the subsequently emerging field of Resilience Engineering.

A number of recommendations to the aviation industry were generated based on the ECOM analysis. Further supporting crew conditions (e.g., through further development of training materials, procedures, display design, etc.) for sensemaking of technical issues and assessing their potential consequences seems warranted. This may include supporting crew to rapidly re-frame and take action following surprise situations (Rankin et al., 2013, 2016), and encouraging regular and frequent interactions between control activities, which seems essential to sensemaking, adaptive capacity, and control.

The ECOM analysis deepens the understanding for the patterns of behaviour performed by the crew, and the interactions between the crew, the technical systems and the environment. The variations and misunderstandings in the use of autopilot and engine management imply that this ability to appreciate risks and time constraints and possibilities goes hand-in-hand with the technical understanding of the complex systems that are difficult to understand in pressed situations, making these joint crew-automation issues rather than issues of individual pilots. Results can thus offer more concrete suggestions for how to improve crew ability to cope with, for example, unexpected multi-failure events. Results from the analyses exemplified in this paper suggest that the industry should improve conditions for pilots’ understanding of technical issues and potential consequences, their ability to detect mismatches, strategies for how to re-frame (Rankin et al., 2013, 2016) and that more training for various kinds of surprising situations is warranted. Further, the results led to the development of “flexible procedures” to help crews make decisions in similar situations (Field et al., 2017).

A variety of crew strategies to cope with the unexpected events have been identified, including both more and less successful adaptations to the dynamic circumstances. Experiential learning in the form of increasing the amount of unexpected events in pilots’ training scenarios is likely beneficial to gain confidence and experience in applying different strategy types. This particularly concerns combinations of multiple failures and surprise situations, as well as circumstances in which procedure application is ambiguous (no or multiple suitable procedures or checklists to choose from).

Further development of ECOM-based or similar classification schemes combining multi-layered control models combining different time horizons and combining feedback and feedforward control with suitable operational terms to study flight crew performance variability is a promising avenue for further research.

CRediT authorship contribution statement

Rogier Woltjer: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Amy Rankin:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ellen Ekström:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Victor Sjölin:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Joris Field:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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Glossary

A330: Airbus A330
A/C: Aircraft
A/P: Auto Pilot
ACARS: Aircraft Communication and Addressing Reporting System
AIP: Aeronautical Information Publication
ALT: Altitude
AMS: Amsterdam Airport
APP: Approach
APT: Airport
APU: Auxiliary Power Unit
ATC: Air Traffic Control
ATHR, A/THR: Autothrust
ATIS: Automatic Terminal Information Service
B747: Boeing 747
BRU: Brussels Airport
CPT: Captain
CSE: Cognitive Systems Engineering
COCOM: Contextual Control Model
DFCP: Desirable Flight Crew Performance
ECAM: Electronic Centralised Aircraft Monitoring
ECOM: Extended Control Model
ENG: Engine
FAIL: Failure
FL: Flight Level
FMC: Flight Management Computer
FMS: Flight Management System
F/O, FO: First Officer
FPL: Flight Plan
G/A: Go-Around
G/S: Glide Slope
GEN: Generator
HDG: Heading
HLD: Hold
HI: High
IDG: Integrated Drive Generator
ILS: Instrument Landing System [Approach]
JCS: Joint Cognitive System
LOC: Localizer
MAP: Missed Approach Procedure
MI: Memory Item
NNC: Non Normal Checklist
PF: Pilot Flying
PM: Pilot Monitoring
QNH: [Actual atmospheric pressure at sea level]
RT: Radio Telephony
RWY: Runway
SEL: Select
SID: Standard Instrument Departure
SPD: Speed
STAR: Standard Terminal Arrival Route
STD: Standard [atmospheric pressure]
TEMP: Temperature
THR: Thrust
TL: Thrust Lever
WX: Weather