Modelling Flight Crew Strategies in Unexpected Events: A Cognitive Systems Engineering Perspective

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Abstract. Highly automated fourth generation aircraft are increasingly common in civil aviation operations. However, there are still times when the flight crew are faced with an unexpected event, and must respond appropriately. In this research the potential for the application of Hollnagel's Extended Control Model (ECOM) as an analysis tool for crew-automation Joint Cognitive System (JCS) performance is demonstrated. The development and application of ECOM analysis to flight simulator experimental data is described, highlighting crew-automation JCS performance at different layers of control. The experiments and method are being used to examine the strategies that flight crew apply to handle unexpected situations, applying and operationalizing theories of sensemaking, macrocognition, and Cognitive Systems Engineering (CSE).

Keywords: Modelling, Sensemaking, Cognitive Systems Engineering, Experiment Analysis, ECOM

Introduction

In Cognitive Systems Engineering (CSE), methods that are used to analyse 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 and technology are studied separately, each seen as one unit of analysis (Woods & Hollnagel, 2006). In CSE, it is the effort of the joint system and the relations between system parts and the phenomena which emerge as a result of system interactions that are of main interest (Hollnagel & Woods, 2005).

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 how we anticipate future events (Klein, Snowden & Pin, 2010; Klein, Wiggins, & Dominguez, 2010; Weick, Sutcliffe, & Obstfeld, 2005). Sensemaking is not only described as an individual process, but can also be described and investigated as a team coordinating their efforts of gathering data and distributing the inferences. Team sensemaking has been defined as "the process by which a team manages and coordinates its efforts to explain the current situation and to anticipate future situation, typically under uncertain or ambiguous conditions" (Klein, Wiggins, & Dominguez, 2010, p 304).

In the research carried out within the Man4Gen project we aim to investigate how crew's adapt their performance to cope with unexpected events. Research focus is on understanding the sensemaking processes taking place as crew cope and includes investigating how the crew search for information, manage uncertainties, prioritise and make trade-offs, assess risks, consider options and anticipate future events. Through identifying the joint systems control strategies we aim to establish the level of adaptation and resilient potential that is required in the cockpit.

In this paper we demonstrate how the ECOM can be used to analyse crew-automation behaviour, and subsequently trace the sensemaking and perception-action processes taking place in the context of the cockpit. Firstly we offer a brief introduction to JCS modelling with a focus on the ECOM. Secondly a short overview of the experiment and data collected is presented, which has been used to operationalise the ECOM. However, the results of the experiment are not within the scope of this paper. Thirdly we describe the process of developing the ECOM to fit the crew-aircraft system and the scenario of the experiment. Finally, we discuss how this type of modelling can offer new insights into describing how the crew-aircraft system maintain control of the aircraft in unexpected situation.

Modelling control of the JCS

The Contextual Control Model (COCOM) (Hollnagel & Woods, 2005) is a cyclical model showing the relation of human perception and action and is at the core of a CSE perspective. The "sensemaking and control" loop demonstrated in Figure 1 is an adaptation of COCOM to the crew-aircraft context (for elaborated description and model see Rankin, Woltjer, Field, & Woods, 2013). The "sensemaking and control" loop demonstrates the cyclical process of how the current Understanding of the situation leads to Actions on the Process to be controlled (light blue). Actions together with External events and Disturbances produce Events in the process, and Feedback. Events/feedback modifies the Understanding of the situation, and the loop continues. In this view, it is the context of the situation that determines the actions and therefore the performance of people. The perception of events and feedback for pilots is mostly from the displays and other interfaces in the cockpit, feeling the movement of the airplane, and looking out of the windows.

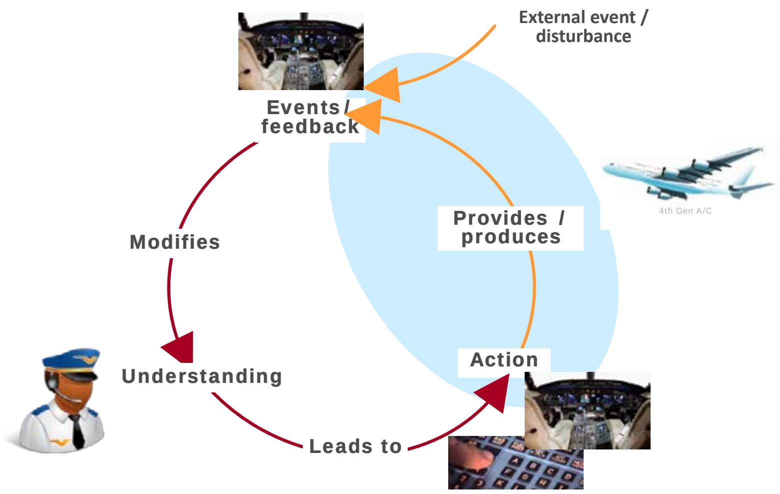

Figure 1 The cyclical model of human action and perception (adapted from Hollnagel, 2002).

In the Extended Control Model (ECOM) described below (Figure 2), cognition is again described as control (Hollnagel & Woods, 2005). The ECOM comprises four parallel control loops, similar to the cyclical model described above (Figure 1), which makes ECOM a multi-layered model of cognition and human action. An extension of the COCOM cyclical model to the crew-automation JCS handling surprising events, as part of this project, has been presented earlier (Rankin, Woltjer, Field, & Woods, 2013). The ECOM model is the basis for analysis in this work and is therefore described in more detail below.

Modelling control through ECOM

The ECOM (Hollnagel & Woods, 2005) is a model to describe multiple layers of performance of the joint crew-aircraft system (illustrated in Figure 2). 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. 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.

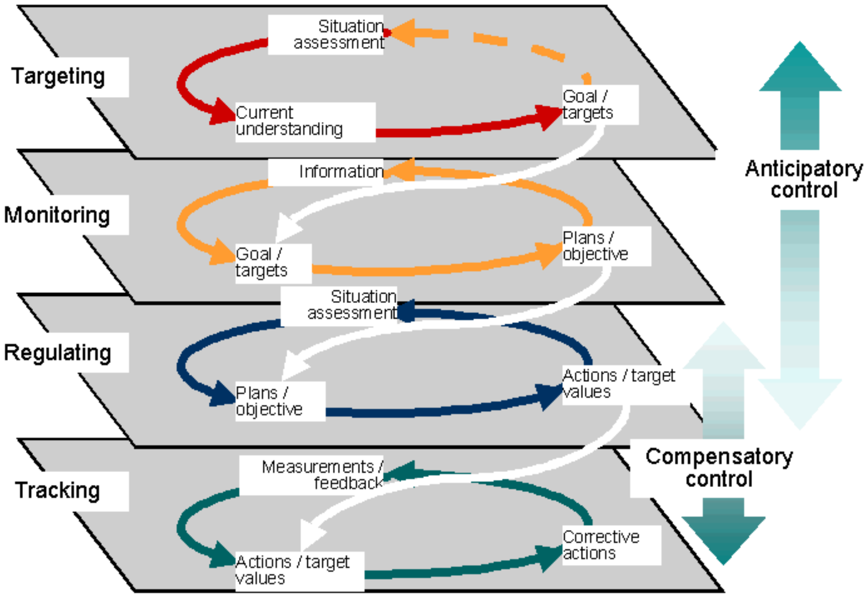

Figure 2. The Extended Control Model, ECOM (Hollnagel, 2002)

This functional account of the joint system recognizes that a systems performance takes place simultaneously on multiple layers of control (Table 1). 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 track performance (e.g., "adjust speed"). The goals set at the targeting layer provides inputs and targets for the monitoring, regulating and tracking layers and reversely the tracking layer provide input to revision of goals and targets. The simultaneous anticipatory (feedforward) and reactive (feedback) control is shaped by the current conditions and system constraints.

Table 1. ECOM layers

Control layer	Description
Targeting	Set and re-evaluate targets; set criteria (efficiency, safety, etc.)
Monitoring (planning)	systematically keeping track of progress, maintain resources, stay within envelope
Regulating	accomplishing state transitions by readily available operations for short-term goals
Tracking	the response of an operator or control system intended to nullify the effects of some external disturbance

Method

Methods for investigating JCS at work (Woods & Hollnagel, 2006) include studying practitioners' operations and work practice, and various kinds of staged world observations, including experiments. Research methods to a higher or lower degree always shape and therefore distort the work processes (e.g., flight operations) they aim to investigate. Therefore, several methods (e.g. observations, interviews, simulations, experiments) may be combined in order to identify, describe and analyse relevant aspects of operational practice. Carefully balancing aspects of "ecological validity", retaining the essential dynamics and intricacies of work practice, and creating scenarios that are meaningful to practitioners, is essential (Woods & Hollnagel, 2006).

Interpreting and analysing observation data from staged world experiments is focused on tracing the process for which the JCS responds to the challenges created in the simulation (Woods & Hollnagel, 2006). A process analysis can, for instance, be carried out as described performance on different levels of abstraction, from raw data, to context specific analysis to a formal and subsequently more conceptual level of description in (for more elaboration see Hollnagel, Pedersen, & Rasmussen, 1981; Woods, 1993). Performance descriptions can subsequently be described and contrasted to cases across scenarios, domains or artefacts, aiding the researcher to abstract patterns of performance (Woods & Hollnagel, 2006).

Experiment

The aim of the experiment was to create an operationally relevant situation for line pilots that would include coping with unexpected events. The intention behind the experiment was to study the flight crew's decision making and risk assessment in response to a situation that they were unlikely to have encountered during routine training. The scenario was designed to include a number of events to address the specific aspects of the project problem statement including: reversion to manual control, a challenging situation and active and authoritative decision making.

The experiment was carried out with a total of 12 crews made up of operational line pilots, 24 pilots in total – both captains and first officers. The crew members were active line pilots, or recently retired, and came predominately from two Western European operators. The crews were unaware of the events in the scenario, and were instructed to treat the scenario as a normal operational flight.

Scenario

The scenario that was flown by the crew was prepared together with operational experts from aircraft manufacturers, training organisations and airline operators. The scenario included three key events that the crew were expected to deal with; 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 and a birdstike causing a failure of engine 1, and engines 3 and 4 to start surging and stalling. The crews carried out an initial approach, where weather conditions resulted in a go-around. The birdstrike occurred after the go-around. The crews were subsequently free to elect the runway to return to, or decide to hold before landing.

Data collection

During the flight video cameras were setup from three different angles to capture the actions and communication of the crew members; one in rear and two in front capturing the individual crew members. Control inputs and display data were recorded. After the experiment was completed, the crew members were instructed not to discuss the flight together, and were interviewed individually. When the individual interview was completed, the crew members filled out individual assessment questionnaires. The final stage of the debriefing was a joint interview using the video recording of the experimental session to discuss the events that occurred in their session.

The main data sources for the JCS analysis during the experiments include: Video data (Cockpit, PFD, ND, RHS, LHS, audio), Display data, Communications, Pilot Flying (PF) interview recording, Pilot Monitoring (PM) interview recording and joint crew interview recording. The video and audio data has been transformed into observation notes capturing communication and key actions of the crews. A list of all action types/communications to be included in the analysis was created used to ensure capturing the same information for each crew. When necessary the display data has been used to complement the observation data. The interview data has been transcribed.

Other data, including eye-tracking, heart rate monitoring, controls data, flight parameters data and self-rating questioners were also captured. Instructor observers were present and qualitative and quantitative instructor ratings have been made. Results from the various analyses taking place within the project will be included and compared to the ECOM analysis carried out.

Results

In this section we describe the process of operationalization of the ECOM, highlighted with examples from the data. First a description of how experiment data was used to identify the ECOM classification is presented. Second, the process of combining data from different sources into the developed classification scheme is demonstrated.

Development of ECOM classifications

To operationalise the ECOM the layers have been defined to fit the context of the crew-automation JCS. Each of the four ECOM layers are described and defined through the experimental data and context. Assigning the observations to the different layers is 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 from two crews were used to develop the classification scheme using three independent raters and iteratively reaching consensus, to then be applied to the remaining datasets. Below we present the operationalization of ECOM through the transition from raw observation data into activity types.

The four ECOM loops

As mentioned in the introduction, each layer in the ECOM is a control loop similar to the model described in Figure 1, which is an action-perception cycle demonstrating the cyclical nature of how external events and understanding of the situation leads to actions, which in turn provides feedback that update the current understanding. Each ECOM loop can thus be described as having *input* (external events, changes in the environment), an *understanding* of the current situation (situation assessment) and *output* (actions taken to control the process). The multiple layers of control loops are used as a means to describe how simultaneous cyclical activities are carried out by the joint system. Each layer therefore corresponds to a different set of activities describing the distribution and simultaneously ongoing tasks and roles of the joint system (an overview of the activities identified at each layer can be found in Table 4).

Relations between the loops

As Figure 2 illustrates, the *output* of each layer feeds directly into the *understanding* at the layer below. The example in Table 3 demonstrates how the activities at a Monitoring layer (identifying the need to go-around based on environmental conditions) affect the activities as a Regulating layer (carry out the go-around by setting/monitoring target values). The environmental "input" into a Monitoring layer includes observations associated with, for example, monitoring the weather and terrain. This *input* is used by the crew to create an *understanding* of the current weather situation. In the example in Table 3 this leads to the identification of the need to go-around based on the deteriorating visibility. The *output* at a Monitoring layer is thus the "trigger" of carrying out the go-around, including selecting actions to fulfil the go-around and inform ATC of the missed approach. In the example below the action to go-around will require an understanding at a Regulating layer of the current values and how these need to be adjusted. The "output" of the Regulating layer will be used to set the target values necessary to fulfil the action of carrying out a go-around. In modern aircraft, these activities are commonly a joint effort by the crew and automated systems, i.e. of the crew-automation JCS. As in all ECOM layers, information is received from environment (context) as input. In this example, *input* to the Regulating layer is a clearance from ATC on missed approach values (e.g., heading, speed).

Table 2. Example of ECOM control loops.

	Example "input"	**Example "understanding"**	**Example "output"**	**Example Activities**
Monitoring	Environmental conditions of current flight (e.g., weather, terrain (MSA), …)	Identify need for go-around based on visibility	Checklist "triggers" (e.g., selection for execution of functions, inform ATC of go-around)	Information retrieval on environmental conditions identify appropriate checklist and briefing Inform ATC of G/A
Regulating	Clearance (receive from ATC + readback) on heading, speed, altitude	Currently set heading, altitude, speed according to plan	Set target heading, altitude, speed, …, Set autobrakes	Set/monitor values for autopilot, ATC clearances

From raw observations to activity types

To achieve a workable classification scheme to use as an analysis tool that ensures consistency of classifications the observations where translated into activities types (Table 4). In column 2 the observation made from the video recordings is presented raw. In this example the captain describes the lack of time to perform any checklist as his focus is on managing the damaged engines. This is classified as part of the activity “prioritizing tasks”. The observations were firstly translated into an activity, described in the contextual setting of the scenario (column 3), and subsequently translated into higher order abstract activities (column 4). This was done for each observation identified in the first two crews to ensure traceability of observations to activities.

Table 3. Example, from data to abstract activities

Control layer	**Trial data (observation/interview)**	**Activities (in context)**	**Activities (abstract)**
Targeting	"no time for emergency checklist, more important to manage engines" (interview data)	Prioritizing tasks (e.g., take time to manage engines, no time for emergency checklist)	Prioritize between goals Anticipate risks / consequences of actions
Monitoring	CPT: "multiple engines stall" (observation data)	Checklist and briefing and memory items "triggers", decision not to do checklist	(Re-) plan and prioritize tasks
Regulating	CPT: "take action" F/O: "engines 1, 3, and 4 in cut-off, and then around" (observation data)	Set/monitor (crew) values	Function allocation of agents/mode to tracking tasks Planning of tracking tasks Recognizing triggers for procedure /checklist /memory items
Tracking	F/O operates thrust levers (observation data)	F/O manual operation of thrust	Operate controls

Table 5 presents an overview of the developed ECOM classification scheme, presenting the abstracted activities at each layer. The activities have also been classified as anticipatory (cf. “staying ahead”, Rankin et al., 2013) or compensatory. A crew continuously demonstrating a high frequency of only compensatory activities could be an indication that they are reactive to their environment with little or no time to plan their next move or anticipate future events. As can be seen in Table 4, preliminary results indicate that the top layers generally involve anticipatory control and the lower layers compensatory control, consistent with Hollnagel & Woods (2005) description.

Table 4. ECOM activities (preliminary results)

Control layer	**Activities (abstract) (compensatory anticipatory)**
Targeting	Anticipatory situation assessment of environmental conditions Consider need to retarget Re-target Prioritize between goals Anticipate risks / consequences of actions
Monitoring	(Re-) plan and prioritize tasks (Re-) plan trajectory Function allocation of agent regulating tasks Monitoring env cond

	Information push/pull on plan and env cond identify/decide process phase
Regulating	Function allocation of agents/mode to tracking tasks Setting values according to plan Monitoring if values are according to plan Monitoring of feedback from tracking Planning of tracking tasks Recognizing triggers for procedure /checklist /memory item
Tracking	Operate controls Monitor controls Monitor sensor values

Combining the data

The observation and interview data for each of the 12 crews were subsequently classified according to the developed ECOM classification scheme. The next step of the process tracing is to combine complementary data sources into a coherent picture of the events and activities taking place. A mapping is performed between the processes described and the research questions defined. The research questions include identifying how the crew's cope with the uncertainties, assess risks and consider options in relation to the scenario events.

The example below demonstrates how observation data is combined with interview data. In this situation the crew are coping with multiple engine failures following a birdstrike. Out of the four engines has failed, one is operating normally and two are surging and stalling.

Observation data

The observation data shows the assessment of the engines carried out by the PM, and the decisions taken by the PF to manage the situation (see extract of observation data Table 6). The PM identifies two different types of problems; engine failure and engine stalling. The PF calls for the engine failure to be addressed, through attempting to restart the failed engine twice. No acknowledgement or further response is seen from the PF related to the stalling engines and the stalling engines are continued to be operated while stalling and surging through the remainder of the flight. The crew decide to return to the airfield and land as soon as possible. During the final stages of the descent prior to landing, when thrust is reduced on all of the engines to manage the speed, the stalling engines stabilize. After landing, when full reverse thrust is used on all engines, they start stalling again.

Debriefing data

The individual debriefing of the crew members highlights the reasoning that the crew had behind their decisions related to the engine assessment and management in this situation (see excerpt in). Both crew members discuss the assessment of the multiple engine failure as a severe situation, and prioritize the need to return to the airfield quickly. The PF and PM also agree that the attempts to restart the engine failed. The PF highlights the risk of losing engines 3 and 4, should they carry out any of the emergency procedures, and as such decide to focus on returning and landing, while operating the engines as they are (stalling and surging). While the PM did identify the required emergency procedure to handle the stalling engines, the PM also agreed with the assessment to return to the airfield as soon as possible.

In the joint interview, using the video recording of the experimental session, the decisions are further discussed between the crew members (see excerpt in Table 8). The PF identifies that once the decisions were made to return to the airfield, and while flying back to the runway, the PF reduces thrust on engines 3 and 4 once satisfied that engine 2 is unaffected. The aim of this, as described by the captain, was to attempt to stabilize the engines, through monitoring some of the affected engine parameters. However, thrust was not reduced sufficiently to fully stabilize the engines, and they continue to stall and surge. The PF also describes flying the aircraft to maintain altitude and speed, such that on the final approach to the runway, the engines could be reduced to idle thrust – which is when they were first stabilized.

Combining the data in the ECOM framework enables us to map out the process of the JCS coping with the multiple engine failures.

Table 5. Excerpt of synthesis of observation data (normal) and interview data (italic)

Tracking	Regulating	Monitoring	Targeting
	PM assesses state of engines, determines engine failure engine 1, stalling surging engines 2 and 3.		
	PF requests restart of engine 1		*PF does not to apply procedures to engines 3 & 4, due to the risk of losing them.*
PM cycles fuel cut-off switch for engine 1.		PF determines return to the same runway – Runway 06.	*PF assesses state of aircraft requires immediate return.*
PF turns to return to Runway 06			
	PM assesses engine state, confirms return to runway with ATC.		
PF reduces thrust on engines 3 & 4 (not enough to stabilise them), but maintains higher thrust to control speed and altitude.			

Automation systems data

In addition to considering the data from the flight crew's actions and intentions, it is useful from a JCS perspective to include the contribution of the automatic flight control systems in the flight path management.

For the aircraft in question, there are several systems that can be used to achieve control of the flight path. At the monitoring level, the Flight Management System is used to determine the flight path details (waypoints, altitudes, speeds) in order to achieve the goals set at the targeting level (the destination and arrival time). At the regulating level, the Autopilot and Autothrottle control the aircraft systems to achieve the required altitude, heading and speed – either from commands from the Flight Management System (in "managed modes") or from commands from the flight crew (using "selected modes"). At the tracking level the Autopilot has modes that hold the current aircraft attitude (pitch and roll) in response to commands from the flight crew.

Using an earlier segment of the crew's flight as in Example 1 this application of the autopilot modes within the ECOM analysis is illustrated in Table 9. At the start of the descent, the aircraft is set up with the route, including the approach route, altitudes and speeds, programmed into the Flight Management System. The autopilot is flying in "managed modes" on commands from the FMS. The PF decides to intervene in the route, and adjust the descent route by switching the autopilot to "selected modes" – using Vertical Speed mode instead. In this way, the PF is achieving the desired vertical profile for the route by commanding the vertical speed and airspeed directly. The PF is monitoring the altitude and speed, and adjusting the commands to the autopilot. The autopilot is monitoring the vertical speed, and adjusting the control surfaces to achieve the commanded vertical speed.

Table 6. Excerpt of synthesis of observation data (normal) and automation data (italic)

Tracking	Regulating	Monitoring	Targeting
	After clearance from ATC, PM confirms the standard arrival route, the weather information and QNH, and descent clearance to 4500 ft.	*Flight Management system determines altitude and speed based on the approach route*	
Autopilot commands surfaces to achieve flight path	PF sets the MCP altitude to 4500 ft to enable autopilot to continue managed descent. *Autopilot follows required modes, altitude and speed from the FMS*		
Autopilot commands surfaces to achieve vertical speed	PF decides to use autopilot Vertical Speed mode, adjusts vertical speed and airspeed command.		
Autopilot commands surfaces to descend to required altitude	PF changes mode to Level Change, setting the target altitude as 4500.		

Identifying patterns across crews

Following the combination of different data sources the next analysis step is to compare the findings across crews. The example in Table 10 demonstrates the risk assessment processes of crew A and B coping with the engine failures after the birdstrike, leading to the decision to land the aircraft. The aim of this joint system analysis is to firstly identify the crew's process of coping with events and not just in terms of actions, but also their reasoning and consideration made. Secondly, we aim to compare the processes identified across the crews to identify patterns and trends in the strategies used to cope with unexpected events.

In examining this section of the scenario some differences can be highlighted. While both crews are involved in the immediate handling of the situation, flying the aircraft and carrying out actions on the engines, there is an apparent difference in the way that the crews prioritise the situation, and consequently the handling actions that they undertake.

Crew A identifies the situation as serious, and the Captain (Pilot Flying) immediately decides to return to the same runway, and takes action accordingly. In Crew B, the Captain (PF) similarly identifies that an immediate return to the airfield is required, but decides first to assess and stabilise the engines, continuing to fly the current heading while the First Officer (Pilot Monitoring) carries out actions on the engines. It is also interesting to note that the first crew prioritises the handling of procedures on the failed engine, while the second crew prioritised stabilising the surging engines. In both cases interviews with the Captains confirmed that their assessment (on a targeting level) considered the options for procedures on the engines.

Table 7. Excerpt of analysis data for Crew B.

Tracking	Regulating	Monitoring	Targeting
	PM assesses state of engines – identifies surge or stall.		
PF confirms, rolls aircraft level.	PF requests autopilot engaged. PM engages autopilot	PF decides to use autopilot to stabilise, while helping identify the problems.	
PF disconnects autopilot, due to lack of heading control[1] – manual control.	PM identifies engine 1 failure, summarises engine 2 normal, engines 3 and 4 surging and stalling.		PF stabilises engines to fully assess situation, while intending immediate return to airfield.
PF reduces thrust on engines 1, 3 and 4.	PF confirms engine state with PM.		
PF reduces thrust to idle on engines 1, 3 and 4.	PF asks for Mayday call.	PM declares Mayday, informs ATC they are maintaining heading.	PM considers engine state, weather conditions options for runways. Stabilise engines, and run emergency procedures.
	PM summarises status, identifies surge/stall procedure: engines 3 and 4 can be increased until surge starts.		
	PF calls memory items be carried out.		
PM increases thrust engines 3 and 4	As PM increases thrust, calls out engine status. Stabilises engines 3 and 4 at below 60%		

The example further demonstrates the importance of combining data sources to gain an understanding of the joint system's performance and distribution of activities across layers of control. We see that in Crews A and B, the primary actions after the multiple engine failure

[1] The heading control function of the autopilot was failed as an earlier element in the scenario.

are assessing the situation and taking actions at a regulatory layer, with the associated activities at the tracking layer. While these activities are primarily compensatory, it is clear from the interviews that the flight crew were actively anticipating further potential events and the effect of the engine failures on their options for returning to the airfield.

The example above demonstrated the use of ECOM analysis in combination with a risk assessment analysis. In a similar fashion several of the areas for analysis can be combined to investigate the different processes of interest in the Man4Gen project. Models and concepts such as "ECOM" or "risk assessment" can be seen as "filters" or theoretical glasses that allow the research question in focus to steer the analysis. In next steps of the analysis other "filters" will be applied to the data to investigate the sensemaking processes. Filters included are, for example, uncertainty, mismatches in understanding (between CPT/FO, crew/system, crew/environment), trade-offs, prioritising goals, subjective assessments (workload, stress, time pressure), compensatory and anticipatory thinking and action and function (re-)allocation. The intention is to combine the analysis of multiple filters to generate patterns of crew performance in relation to the scenario events.

Discussion

We have demonstrated the analysis of the crew-automation Joint Cognitive System (JCS) performance in flight simulator experiments and the potential for the application of Hollnagel's Extended Control Model (ECOM). The ECOM analysis demonstrates how compensatory and anticipatory functions and activities play out on multiple control layers simultaneously and how they affect each other.

Preliminary results of this CSE analysis show how various data sources (observations, communication analysis, debriefing, and automation use) can be jointly interpreted in a process tracing method (cf. Woods, 1993) so as to establish a description of the performance of the crew-automation JCS. By combining different sets of data, several stories come into play, such as reasoning behind actions and mismatches between the crew members or interpretations of what the automated systems are doing. We argue that such compilation and interpretation of multiple data sources is necessary for addressing the JCS performance to a satisfactory extent. Once fully developed, this function-oriented methodology aims to extend the methods of aviation psychology and human factors beyond the more traditional views and methods that tend to focus on single operators or crews.

Tagging the data using ECOM layers offers unique insight into the multiple processes going on simultaneously in the cockpit. By capturing the process it is possible to analyse and identify how time, uncertainty, trust, risks and contextual factors affect the actions taken and the decisions made. In this paper an example of this was provided, demonstrating how two crews assess risks regarding a multiple engine failure.

The experiments and method described in this paper are being used to examine the strategies that flight crew apply to handle unexpected situations, and decide on appropriate actions in response to the events, including flying the aircraft manually, applying and operationalizing theories of sensemaking and Cognitive Systems Engineering (CSE). This ECOM analysis method has been developed to be a representation with the potential of identifying, describing, and connecting the identification and analyses of patterns using central concepts in sensemaking, macrocognition, and CSE research.

References

Furniss, D., Back, J., Blandford, A., Hildebrandt, M., & Broberg, H. (2011). A resilience markers framework for small teams. *Reliability Engineering & System Safety*, *96*(1), 2–10. doi:10.1016/j.ress.2010.06.025

Hollnagel, Erik, & Woods, D. (2005). *Joint Cognitive Systems: Foundations of Cognitive Systems Engineering*. Boca Ranton: CRC Press, Taylor & Francis Group.

Hollnagel, Erik, Pedersen, O. M., & Rasmussen, J. (1981). *Notes on human performance analysis*.

Hollnagel, Erik. (2002). Understanding Accidents - From Root Causes to Perfromance Variability. *Proceedings of the IEEE 7th Conference of Human factors and Power Plants* (pp. 1–6). Scottsdale, Arizona.

Klein, G., Snowden, D., & Pin, C. L. (2011). Anticipatory thinking. *KL Mosier, & UM Fischer, Informed by Knowledge*, 235-246.

Klein, Gary, Wiggins, S., & Dominguez, C. O. (2010). Team sensemaking. *Theoretical Issues in Ergonomics Science*, *11*(4), 304–320.

Kontogiannis, T. (1999). User strategies in recovering from errors in man ± machine systems. *Safety Science*, *32*, 49–68.

Mendonça, D., & Wallace, W. (2004). Studying Organizationally-situated Improvisation in Response to Extreme Events. *International Journal of Mass Emergencies and Disasters*, *22*(2), 5–30.

Mumaw, R., Sarter, N., & Wickens, C. (2001). Analysis Of Pilots Monitoring and Performance on an Automated Flight Deck. *Proceedings of the 11th International Symposium on Aviation Psychology*. Colombus, OH.

Neisser, U. (1976). *Cognition and Reality: Principles and Implications of Cognitive Psychology*. San Francisco, CA: W. H. Freeman and Company.

Rankin, A., Lundberg, J., Woltjer, R., Rollenhagen, C., & Hollnagel, E. (2014). Resilience in Everyday Operations: A Framework for Analyzing Adaptations in High-Risk Work. *Journal of Cognitive Engineering and Decision Making*, 8(1), 78–97.

Rankin, A., Lundberg, J., & Woltjer, R. (in press). A Framework for Learning from Adaptive Performance. In C. P. Nemeth & E. Hollnagel (Eds.), *Resilience Engineering in Practice, Volume 2, Becoming Resilient*. Aldershot, UK: Ashgate.

Rankin, A., Woltjer, R., Field, J., & Woods, D. (2013). "Staying ahead of the aircraft" and Managing Surprise in Modern Airliners. In I. Herrera, J. M. Schraagen, J. Van der Vorm, & D. Woods (Eds.), *Proceedings of the 5th Resilience Engineering Association Symposium* (pp. 209–214). Soesterberg, NL: Resilience Engineering Association.

Weick, K. E., Sutcliffe, K. M., & Obstfeld, D. (2005). Organizing and the process of sensemaking. *Organization science*, *16*(4), 409-421.

Woods, D. D. (1993). Process-tracing methods for the study of cognition outside of the experimental laboratory. In G. A. Klein, J. Orasanu, R. Calderwood, & C. E. Zsambok (Eds.), *Decision making in action: models and methods* (pp. 228– 251). Norwood, NJ: Ablex.

Woods, D., & Hollnagel, E. (2006). *Joint Cognitive Systems Engineering*. *Group*. Boca Raton, FL, US: CRC Press, Taylor & Francis Group.

Acknowledgments and Contact Information

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