Safe limits, mindful organizing and loss of control in commercial aviation

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Abstract

In commercial aviation, loss of control (LOC) incidents are currently the single biggest cause of accident fatalities. Although LOC incidents typically have multiple causes, inappropriate flight crew responses to unfamiliar conditions are a major contributor. It has been suggested that restricted exposure to unusual aircraft behavior and limited manual flying are partly responsible for this, both of which are aggravated by high levels of flight deck automation. In this paper, we draw on ideas from human-automation interactions, organizational limits, mindful organizing and sensemaking to explore how systems that are very safe by design may subtly undermine mindful organizing, reducing the ability of operators to handle unusual and expected situations. We discuss “the paradox of almost totally safe systems” (Amalberti, 2001) and argue that as systems become safer by design it is increasingly difficult for operators to handle for unusual, extreme events, partly due to an erosion of mindful organizing, partly to the limitations of existing training and simulation.

Keywords: Organizational limits; Mindful organizing; Loss of control; Aviation safety; Automation

Introduction

The organizational attributes of safe, reliable systems have been of interest to scholars for many years. There has been a long running debate between those who consider occasional accidents to be normal and inevitable in complex, tightly coupled systems (Perrow, 1984) and those who maintain that some forms of organization permit near error-free operation despite complexity, tight coupling and trying conditions. The latter position is represented by scholars of “high-reliability organizations” (HROs) who have identified a set of organizations that are able to operate complex, hazardous systems to remarkably high levels of safety and reliability (LaPorte and Consolini, 1991, Weick and Roberts, 1993, Rijpma, 1997, Roe and Schulman, 2008, Weick and Sutcliffe, 2007). A key attribute of HROs is their capacity for “mindful organizing” or “collective mindfulness”, construed as a state of shared awareness and attention that emerges from interactions between multiple actors, “a totality with intricately connected and interdependent components, from which organizational mindfulness emerges at the system level” (Carlo et al., 2012, p.1102).

However, even highly reliable systems have accident rates that plateau at around five major accidents per 10^{-7} safety units of the system, a phenomenon that has been labelled “the paradox of almost totally safe systems” (Amalberti, 2001). This suggests that there are some types of accidents that even HROs cannot completely eliminate.

In commercial aviation, “loss of control” (LOC) incidents fall into this category of difficult-to-eliminate accidents. LOC is currently the single greatest cause of casualties in commercial aviation. LOC is defined as aircraft motion that is outside of the normal flight envelope, is not predictably altered by pilot actions and is characterized by an inability to maintain aircraft parameters such as heading and altitude (Belcastro, 2012, RASFOG, 2010). LOC accounted for nearly 2,000 fatalities in 22 fatal air accidents between 1999 and 2008 (Boeing, 2009) and 37 fatal accidents and 1,242 fatalities (43% of all fatalities) between 2010 and 2014 (IATA, 2015).

LOC incidents are typically the result of multiple events and conditions which interact in unpredictable and unforeseen ways. An analysis of 275 LOC incidents between 1996 and

2010 found that LOC was usually caused by a combination of onboard events and external hazards (Belcastro et al., 2014). System failures and inappropriate crew actions were the most significant factors. A more recent analysis of 38 fatal LOC accidents reached similar conclusions, noting that whilst the initial trigger to an incident was often external to an aircraft:

> "Human performance deficiencies, including improper, inadequate or absent training, automation and flight mode confusion, distraction, the 'startle' factor and loss of situational awareness frequently compounded the initial upset and precluded an effective recovery until it was too late" (IATA, 2015, p.25).

Most types of aviation accidents have declined over time, but LOC incidents have not (Boeing, 2009, IATA, 2015). This is a source of concern within the aviation community. Analyses of LOC events have raised suspicions that the sector's very success in achieving predictability and control of operations, particularly through flight deck automation, may in fact be part of the problem. Flight deck automation has played a huge role in reducing accidents due to pilot error, but has also reduced the exposure of pilots to unusual aircraft behavior and, more generally, their mental engagement with many of the details of the operation of their aircraft (Harris, 2011, Harris, 2014, Rochlin, 1997, Learmount, 2011):

> "When aeroplanes didn't have flight management systems pilots had to work out their navigation and aircraft performance on paper. Planning a complex descent in difficult terrain while flying on instruments would require a combination of mental arithmetic and the use of pages of tables in the flight manual, or the use of a circular slide rule, or both. The effect of doing these things with raw data meant that the pilots were more mentally engaged in the aircraft's trajectory planning than they are now" (Learmount, 2011).

Commercial aviation operates to extraordinary levels of safety under almost all conditions, but nonetheless flight crews are sometimes unable to deal with unusual combinations of circumstances that are difficult to diagnose and do not lend themselves easily to procedural solutions (RASFOG, 2010, Brooks, 2010, Belcastro, 2012).

In this paper, we explore this problem in three ways. First, we briefly summarize and integrate ideas from three areas of research, from a) research on interactions between automation and human operators, specifically drawing on the idea that automation may 'insulate' teams of operators from the systems that they oversee; b) the literature on organizational limits, which observes that the establishment of ‘limits’ is an important strategy in the pursuit of safety, but one which can come with unwelcome side effects; and c) the literature on mindful organizing and sensemaking, which addresses how humans individually and collectively interpret and respond to complex, dynamic, ambiguous environments. We combine these ideas into a framework in order to explore the paradox of totally safe systems in general and the loss of control problem in particular. Second, we use this framework to guide our analysis of the loss of Air France 447, a particularly vivid example of a LOC accident. Finally, we discuss the relationships between system design and mindful organizing. We do so in order to further understanding of the significance of mindful organizing in complex, safety-critical systems and of how mindful organizing may be subtly undermined by other system-safety strategies. Our purpose is to contribute to the dialogue about how problems such as the LOC problem in commercial aviation may be alleviated.

Human-Automation Interactions

Advances in technology have had a significant impact on aviation, both in the cockpit and in the wider system of commercial aviation. We focus on technology onboard the aircraft itself, where the term the ‘glass cockpit’ describes the automation of many activities previously undertaken directly by pilots (Rochlin, 1997). The term encompasses a range of technologies that collect, process and integrate data and present them to flight crew, usually via electronic displays. In fly-by-wire systems, technology mediates between flight crew inputs and aircraft responses, for example by preventing manoeuvres that might overstress the airframe or otherwise endanger the aircraft and, via the flight control system, controls the aircraft automatically for much of the time. This means that pilots spend much time monitoring aircraft systems than directly flying the aircraft.

These developments have supported the huge expansion of commercial aviation in recent years and have brought many safety benefits. By the late 1990s glass cockpit aircraft had an accident rate that was half that of the previous generation of aircraft. The time required for pilot training has fallen dramatically; crews are smaller and fuel efficiency is higher (Amalberti, 1998, Harris, 2014).

However, cockpit automation comes with certain side-effects, most notably in terms of its impact on the cognition of those who operate it (Rochlin, 1997, Learmount, 2011). Cockpit automation takes flight crew out of the loop for a high proportion of the time, raising concerns that it may erode their ability to rapidly grasp unusual, highly demanding, situations (Endsley, 1996, Adams et al., 1995). It can be difficult for operators to understand exactly what complex, automated processes are actually doing in the event of a malfunction or anomaly, yet there may be very little time to make a diagnosis and respond (Young et al., 2006, Harris, 2011, Learmount, 2011, Rochlin, 1997). During an 'automation surprise' (Wiener, 1989, Miller and Woods, 1997) there can be a:

> "Breakdown in the coordination between crew and automated systems…The complexity of, and interactions across, automated systems [have] led to situations where the crew's perceptions of what the automation would do and what it was actually doing were different" (Miller and Woods, 1997, p.144).

When confronted by automation surprises crews may have a very short critical window during which to work out what the technology is doing and what it will do next (Weick et al., 1999, Miller and Woods, 1997). Thus, humans may struggle to establish control of the system, especially if the automation has been doing much of the thinking and acting on their behalf prior to the surprise.

Organizational Limits

The concept of organizational limits is based on the idea that organizations, systems and other units have limits to what they are capable of doing (Farjoun and Starbuck, 2007, Starbuck and Farjoun, 2005, Oliver et al., 2017). 'Limits' refer to the "range, amount, duration, and quality of things [organizations] can do with their current capabilities, and these limits may originate in their members' perceptions, in their policies, in the technologies they adopt, or in their environments" (Farjoun and Starbuck, 2007, p.543). The concept of limits emerged from an analysis of the loss of the space shuttle Columbia, which concluded that

NASA had “pushed or been pushed to the *limit* of what an organization can accomplish” (Starbuck and Farjoun, 2005, p.360). In this context, the concept of a limit denotes constraints on what can be safely achieved within a given set of resources; when these constraints are exceeded, negative, consequences are likely to follow. Physical structures and systems may collapse if subjected to forces beyond the limit of what they can withstand. The concept of organizational limits applies the same principle to human systems, where the “limit” beyond which things go wrong is usually the system’s capacity to absorb, process and respond appropriately to demands from the environment or from subunits of the system itself.

Most systems have “hard” limits to what they can do. Often these are governed by laws of nature and violation of these limits may result in catastrophic failure. To avoid this, system designers construct “soft” limits in the form of rules, policies, operating procedures, safety margins, fool-proofing, fail-safe features and other safeguards to keep systems well within the zone of safe operation, thereby preventing catastrophic violations of hard limits. For aviation, as with many other safety-critical activities, a multitude of policies and protocols function in this way. Technology also performs a limits function. For example, fly-by-wire flight management systems prevent the execution of potentially dangerous manoeuvres that pilots may mistakenly command.

However, venturing close to, or even exceeding, limits can also have an upside. Risk and uncertainty are higher, which usually engenders greater alertness. This can result in enhanced awareness, exploration, learning and capability development. Limit violations expose and update understanding of what is possible and what is not, hence generating knowledge about systems and their behavior (Farjoun and Starbuck, 2007). This implies that systems that (almost always) operate well within their limits increase the risk of inappropriate responses by their operators in the face of unusual conditions – because opportunities for operators to accumulate knowledge of such conditions are limited.

A limits perspective thus provides a clue to the paradox of almost totally safe systems. Hazardous systems must stay within certain parameters if they are to operate safely. Their designers and operators therefore establish limits and work hard to maintain activities within these limits. However, this can “reduce the end user’s cognitive experience of the system and jumble his meta knowledge, confidence, and protective signals when approaching boundaries” (Amalberti, 1998, p.9). It is this reduced “cognitive experience of the system” that has implications for the capacity of crews to organize mindfully.

A limits perspective is therefore useful in theorizing some of the effects of automation described in the previous section. Automation may prevent actors from venturing beyond, or even close to, safe limits, for example when it intervenes automatically between human inputs and system responses. But in doing so, automation may be “masking cognitive signals and impoverishing the efficiency of meta-knowledge, therefore causing the potential for new categories of human losses of control” (Amalberti, 1998, p.7). This highlights the interplay between automation and human cognition, and it is to this issue that we now turn.

Mindful Organizing and Sensemaking

Sensemaking refers to the cognitive and social processes that organize cues into interpretations (Weick, 1979). Sensemaking has been defined as “the process by which we develop an appropriate mental model of a situation that allows us to process information and make intelligent choices” (Olcott and Oliver, 2014, p.8). Much of the work on sensemaking that addresses safety-related issues focuses either on a) disasters, in which failures of sensemaking lead to escalating chains of errors or b) organizations that are able to operate with remarkably few errors, despite operating complex, high-risk technologies under demanding conditions. In both cases, the emphasis is on how actors collectively develop and sustain valid, nuanced interpretations of the situation they face (or fail to do so) and how these interpretations shape their actions.

Examples of sensemaking analyses of catastrophes include the Bhopal chemical disaster (Weick, 1988, Weick, 2010), the Tenerife air disaster (Weick, 1990), the Mann Gulch wildfire (Weick, 1993) and an accidental shooting during an anti-terrorist operation (Colville et al., 2013). In all these tragedies actors failed to read the situation correctly and therefore acted inappropriately. These were often collective, not just individual failures of sensemaking, for example, when some actors dismissed the legitimate concerns of others, thereby shutting down enquiry or when information that was in the system failed to reach those who could act on it. Ambiguous and novel conditions, which by their very nature do not fit readily into existing classificatory schemes, pose particular challenges for collective sensemaking due to the absence of an established and shared language with which to discuss them (Maitlis and Christianson, 2014). When interdependent actors cannot create and maintain valid, shared mental representations of the situations that they face, their ability to process information and take appropriate and coordinated action is inhibited (Weick, 1995). Cues may be missed, misinterpreted or not passed on to others. Early warning signs may be discounted or explained away (Weick, 1988, Weick, 2010).

Sensemaking-related analyses of HROs have included aircraft carriers (Weick and Roberts, 1993, LaPorte and Consolini, 1991, Weick and Sutcliffe, 2001), electricity grids (Roe and Schulman, 2008), nuclear submarines (Bierly and Spender, 1995), firefighting crews (Bigley and Roberts, 2001) and military aviation (Frigotto and Zamarian, 2015). The connection between sensemaking and HROs stems from the fact that HROs exhibit very well-developed “ways in which diverse but stable cognitive processes interrelate in the service of the discovery and correction of errors” (Weick et al., 1999, p.36). This ability highlights the importance of collective cognition and is supported by five attributes or processes, namely 1) preoccupation with failure; 2) reluctance to simplify; 3) sensitivity to operations; 4) commitment to resilience; and 5) deference to expertise (Weick and Sutcliffe, 2007, Weick and Sutcliffe, 2001, Weick et al., 1999).

These processes underpin collective mindfulness and mindful organizing which Sutcliffe, drawing on Weick et al. (1999), defines as a "macro level pattern of collective daily processes and organizing practices that help people to focus attention on perceptual details that are typically lost when they coordinate their actions and share their interpretations and conceptions" (Sutcliffe, 2018, p.70-71).

Weick et al. also use the term “mindful infrastructure” to encompass the five processes, the collective mindfulness that they foster and the resulting capacity of teams and organizations to detect and correct errors. Effective sensemaking does not necessarily underpin all five attributes, but it is clearly relevant to many of them, for example enriched awareness, sensitivity to cues, openness to phenomena that cannot readily be classified and a preparedness to share and combine information across organizational boundaries. “Perceptual details” also encompass the cues and actions of other actors in the system, expressed in concepts such as “heedful inter-relating” and “collective mind” where “collective mind is conceptualized as a pattern of heedful interrelations of actions in a social system” (Weick and Roberts, 1993, p.357). Collective mind requires individuals who form part of a joint-activity system (such as a flight crew) to act towards or “contribute” to the system in the light of a “representation” of how their actions and those of others interrelate. Also necessary is a willingness to “subordinate” one’s actions and preoccupations to the interests and health of the system as a whole (Weick and Roberts, 1993).

As work on HROs has evolved, the term “mindfulness” has increasingly been used to describe the capability that is induced by these features , variously appearing as “mindful infrastructure”, “collective mindfulness”, “organizational mindfulness” and “mindful organizing” (Sutcliffe et al., 2016, Weick et al., 1999). All these terms emphasize the joint cognitive effort required to bring together diverse informational inputs and coordinate multiple, interdependent actors. A state of collective mindfulness enables units within HROs to perceive, interpret and respond appropriately to threatening conditions, preventing such conditions from escalating into full-blown crises. Mindful organizing ascribes a crucial role to individual and social processes of cognition in the maintenance of safe, reliable operation and is consistent with the sensemaking perspective in Weick et al.’s analyses. Thus, sophisticated, shared cognition underpins the successful operation of HROs just as its absence often precedes disaster (Weick, 1993, Weick and Roberts, 1993, Weick, 1988, Weick, 2010, Starbuck and Mas-Tur, 2015).

More recently, research has examined mindful organizing in settings beyond those of traditional HROs (Sutcliffe et al., 2016, Weick and Sutcliffe, 2006, Levinthal and Rerup, 2006, Rerup and Levinthal, 2014, Argote, 2006, Vogus and Sutcliffe, 2012). Much of this research treats mindful organizing as very closely allied to, sometimes synonymous with, the five attributes of HROs mentioned previously. For example, in a review which identified 19 papers containing definitions of "collective mindfulness" (Sutcliffe et al., 2016), 11 of them explicitly invoke the five principles identified in Weick et al.'s 1999 work (or later developments of it) in their definitions. The other eight definitions emphasize alertness, active and continuous assessment of assumptions and nuanced appreciation of context (Hales et al., 2012, Knox et al., 1999). Given the focus of this paper on LOC incidents, we adopt Sutcliffe's 2018 definition, reproduced above, as this encapsulates notions of attention, perceptual detail and coordinated action, all highly relevant to diagnosing and responding to unusual and unexpected events.

Figure 1: Automation, Limits and Mindful Organizing

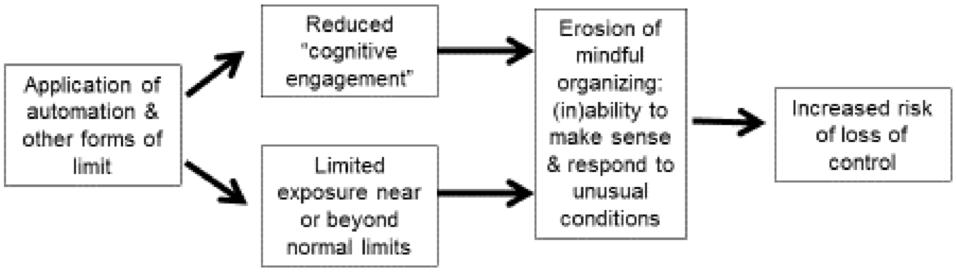


Figure 1 summarizes the main aspects of automation, limits and mindful organizing that we have covered so far and combines them into a simple model for the purpose of this paper. By their very nature, unusual or extreme events trigger enhanced demands for sensemaking and thereby a need for mindful organizing. In complex systems, such events are likely to comprise multiple interacting elements, possibly in combinations not seen before. They are therefore prone to misclassification and misinterpretation and may be difficult to communicate to others.

Automation and other types of limits may influence mindful organizing in a number of ways. Automation, in the form of the glass cockpit, reduces the need for direct, constant engagement between pilots and their aircraft. Sometimes automation may behave in ways that are unexpected and difficult to understand (i.e. “automation surprises”), masking what is actually happening and providing misleading or ambiguous cues. This strains sensemaking capability and makes accurate diagnosis more difficult. Policies, procedures and automatic protections (such as flight envelope protection) that keep aircraft within safe limits also limit the exposure of pilots to the full repertoire of potential aircraft behavior. Together, these conditions can encourage routinization and erode the ability of crews to interpret and respond to rare, unusual situations (Martínez-Córcoles et al., 2014, Martínez-Córcoles, 2018).

Collective mindfulness or mindful organizing is not of course the only determinant of rapid and appropriate responses but it is a significant component, particularly during the “noticing” and “bracketing” stages of diagnosis when situational classification and recognition of the significance and meaning of key cues is crucial (Maitlis and Christianson, 2014). Mindful organizing is also vital during the response phase when close communication and coordination between interdependent actors is necessary - especially if there is only a short window of time within which to effect a recovery. This is consistent with Amalberti’s observations on the importance of “dynamic cognition” and a capacity for “meta-knowledge and error recovery” when crews have to deal with unusual and unexpected conditions (Amalberti, 1998).

Thus, in situations beyond normal limits, mindful organizing is likely to be severely challenged, because the cognitive, coordination and other skills needed to operate beyond these limits have not previously been required or, possibly, even practiced in a real-life environment. Yet it is during such limit violations that mindful organizing and the rapid and effective sensemaking on which it is based are most needed to avert catastrophe (Reason, 2000, Richardson, 1995, Sastry, 1997).

In the next section we describe the loss of Air France 447 in order to illustrate the challenges that extreme, out-of-limits conditions pose for mindful organizing and sensemaking. This analysis is based on the official report on the accident (BEA, 2012), and a book on the loss of AF447 (Palmer, 2013). The official report contains the transcript of AF447's cockpit voice recorder (CVR) and the record of the flight data recorder (FDR). In order to produce a detailed, sequenced record of what occurred on the flight deck of AF447, we extracted four streams of information from these two sources. These were:

(1) The transcript of the CVR
(2) The data from the FDR
(3) The commentary and analysis in the official report
(4) Palmer's commentary and elaboration of the contents of (1) and (2).

Verbatim extracts from each source were placed in one of four columns (CVR, FDR, Official Report, Palmer) in approximate chronological order from the start of the flight up to the crash. Two further columns were then added, one for the precise times at which events occurred, and one for altitude of the aircraft and how this changed over time. The material was then sequenced into a precise chronological order in order to arrive at a picture of how external conditions, individual and collective pilot cognition and the aircraft's technology interacted throughout the episode.

The Loss of Air France 447

Air France flight 447 (AF447) crashed on a night flight from Rio to Paris in 2009 with the loss of all 228 passengers and crew on board. AF447 was about 3.5 hours into its journey, cruising at 35,000 feet on autopilot, when it entered a tropical storm. There were three flight crew on board; the Captain, Marc Dubois (aged 58, 10,988 flight hours), who had left the cockpit for a routine break a few minutes before the aircraft entered the weather system, and two first officers, David Robert (aged 37, 6,547 flight hours) and Pierre-Cedric Bonin (aged 32, 2,936 flight hours). Bonin, the more junior of the two first officers, was designated as the pilot flying and therefore the relief captain. Bonin had showed signs of unease as the plane had approached the weather system and repeatedly expressed his wish to climb to avoid it, but this was not possible due to outside air temperature and the amount of fuel that the aircraft was still carrying at that point in the flight.

As the aircraft entered the storm, the sound of ice particles could be heard on the cockpit voice recorder (CVR). These temporarily blocked the pitot tubes that provide data on airspeed to the flight control system. This caused the autopilot and auto thrust to disconnect, as they were programmed to do when they detected unreliable data. The flight control system switched into “alternate law”, also as programmed, which meant that much of the automatic protection available under “normal law”, such as flight envelope protection, was withdrawn, rendering the aircraft much more sensitive to pilot actions.

The flight data recorder (FDR) shows that the indicated airspeed on one instrument fell from 275 to 60 knots and on the other from 275 to 139 knots, quickly rising to 223 knots. The flight director bars, which are displayed on screens in front of the pilots, disappeared for about 10 seconds. These bars provide guidance to pilots, for example whether to climb or descend. The loss of speed indications also briefly caused a false indication of a decrease in altitude of 330 feet and a downward vertical speed of 600 feet per minute.

These events triggered aural warnings and a series of abbreviated messages were displayed on a screen in front of the pilots. The extract in Table 1 conveys the scene on the flight deck during the first 30 seconds following the autopilot disconnection.

Bonin took manual control of the aircraft, controlling it via a side-stick and calling out “I have the controls”. Turbulence at the moment of disconnection caused the aircraft to roll slightly to the right. Bonin attempted to correct this but did so too aggressively causing the aircraft to roll left and right several times. The side stick touched the left stop at one point, indicating the extremity of Bonin's actions. He also pulled back on the stick which caused the aircraft to pitch up, triggering the aural stall warning to sound three times (02:10:10).

Table 1: CVR transcript of the first 30 seconds after autopilot disconnection

Time (UTC)	Source	Pilots/ Aircraft Instruments
02:10:03	Aircraft:	Cavalry charge [autopilot disconnection warning]
02:10:06	Bonin:	I have the controls
02:10:07	Robert:	Alright
02:10:10	Aircraft:	C-Chord; Stall, stall, stall
	Robert:	What is that?
02:10:13	Bonin:	We haven't got a good…
	Aircraft:	C-chord (for 1 second)
02:10:14	Bonin:	We haven't got a good display… of speed
	Aircraft:	Single chime, single chime, C-chord starts and continues until 2:10:51
	Robert:	We've lost the the the speeds so… [reading out the ECAM[1] messages] engine thrust A T H R [A/THR = auto-thrust] engine lever thrust…
02:10:20	Robert:	[reading the ECAM] … … alternate law protections- (law/low/lo)[2]…
	Bonin:	Engine lever?
02:10:27	Robert:	Watch your speed, watch your speed
	Bonin:	Okay, okay, okay I'm going back down
	Robert:	Stabilise
	Bonin:	Yeah
02:10:32	Robert:	Go back down. According to that we're going up. According to all three you're going up so go back down
	Bonin:	OK

[1] ECAM denotes 'Electronic Centralized Aircraft Monitoring'. This is a display which displays information about aircraft status.

[2] Robert was probably in the middle of saying "Alternate law – protections lost" when Bonin interrupted him.

At the point of disconnection, the situation was quite benign. The speed readings were unreliable and the task of the pilots was to maintain the flightpath manually until they worked out exactly what was going on and formulated an appropriate response. A simulation conducted after the accident demonstrated that the aircraft would have more or less maintained its altitude and attitude in the absence of any action by the pilots. However:

> "The PF [the Pilot Flying i.e. Bonin] was immediately absorbed by dealing with roll, whose oscillations can be explained by a large initial input on the sidestick under the effect of surprise [and by] the continuation of the oscillations, in the time it took to adapt his piloting at high altitude, while subject to an unusual flight law in roll. […] The PF's inputs may be classified as abrupt and excessive. The excessive amplitude of these inputs made them unsuitable and incompatible with the recommended aeroplane handling practices for high altitude flight" (BEA, 2012, p.172).

The accident investigation concluded that between them Bonin and Robert built a partial picture of the situation within the first few seconds following the autopilot disconnection, indicating that they made some progress towards the “system representation” condition identified by Weick and Roberts. This picture incorporated the anomalous speed indications, but it is doubtful that the two pilots fully understood the situation at this point. They did not classify it as an “unreliable speed indication” situation and consequently were jointly unable to invoke the appropriate procedure. They were close to this in the first few seconds - Bonin observed that “We haven’t got a good display… of speed” and Robert was building on this: “We’ve lost the the the speeds so…”). There was also some structure to their initial contributions, with Bonin calling out that he had control, and Robert reading out the information on displayed on the ECAM, but this was soon lost as Robert became distracted by other issues caused by Bonin’s excessive movements of his sidestick.

Robert’s reading of the information displayed on the ECAM demonstrates an attempt to build a representation of the situation, but as the extract from the CVR shows, he was still in the middle of this when he detected the climb caused by Bonin and was drawn into issuing instructions to try to correct this (“Watch your speed, watch your speed”). Robert did not then return to the messages on the ECAM. Despite acknowledging Robert’s instructions to descend (“Okay, okay, okay…”), Bonin maintained the climb, though less steeply than before, meaning that Bonin was making a critical ‘contribution’ to the situation of which Robert was unaware. At 02:10:27 the flight directors reappeared and were now providing guidance for a climb, a response to the persistence of Bonin’s nose-up inputs. From 02:10:50 Robert’s attention switched to trying to recall Captain Dubois to the cockpit, indicating that he had temporarily abandoned trying to develop a representation of the system himself.

At 02:10:51 the aircraft approached 38,000 feet and reached the edge of its flight envelope. The stall warning began to sound again and the CVR recorded vibrations which were almost certainly buffet associated with the onset of an aerodynamic stall. Bonin continued to make nose-up inputs and the aircraft stalled and began a rapid, rolling, yawing descent with its nose pointing upwards. The official report notes that “At this point, only descent of the aeroplane through a nose-down input on the sidestick would have made it possible to bring the aeroplane back within the flight envelope” (BEA, 2012, p.179). Palmer observes that “The situation was then far beyond any training ever practiced in the simulator, or even imagined” (Palmer, 2013, p.2362).

The situation was now critical. The stalled aircraft would take less than four minutes to descend to the ocean and any recovery manoeuvre would consume a significant amount of time and altitude:

> “Only an extremely purposeful crew with a good comprehension of the situation could have carried out a manoeuvre that would have made it possible to perhaps recover control of the aeroplane. In fact, the crew had almost completely lost control of the situation” (BEA, 2012, p.182).

Captain Dubois re-entered the cockpit at 02:11:42 but initially he too was unable to develop a representation of the situation, in part because he too was unaware of Bonin’s contribution. As the plane passed through 20,000 feet, about two and a half minutes after the disconnection, the inability of the crew to understand exactly what was happening to their aircraft is clear from the CVR transcript, in which they appear to be unsure even about whether the aircraft was climbing or descending (see Table 2).

In the absence of the crucial classification of the situation as a deep stall (something which is impossible under normal circumstances) the crew were unable to interpret the cues that were confronting them – in other words, they experienced a classic failure of sensemaking. Dubois’ exclamation of “*It’s impossible*” is indicative of his inability to recognize and classify the situation. Although Bonin and Robert, in theory, held some knowledge about how the situation had developed, they were apparently unable to impart this to Dubois.

Table 2: CVR transcript two minutes and 25 seconds after autopilot disconnection

02:12:27	Aircraft:	Stall
	Robert:	You're climbing
	Aircraft:	Stall
	Robert:	You're going down down down
	Dubois:	(*) (going down)
	Aircraft:	Continuous C-chord
02:12:30	Bonin:	Am I going down now?
	Robert:	Go down
	Dubois:	No you climb there
02:12:33	Bonin:	I'm climbing okay so we're going down
	Dubois:	You're climbing
	Aircraft:	End of C-chord
02:12:34	Aircraft:	Stall, stall
02:12:35	Aircraft:	Cricket, continuous C-Chord
02:12:39	Bonin:	Okay we're in TOGA [ie a high power setting]
02:12:40	Aircraft:	Stall, stall
02:12:42	Bonin:	What are we here? On alti what do we have here?
	Aircraft:	Cricket, stall
02:12:44	Dubois	(expletive) it's impossible
	Aircraft:	Stall, cricket

As the crisis deepened, the crew progressively de-structured, demonstrating a collapse of the coordinated, interactional elements of mindful organizing. Bonin misinterpreted the buffet caused by the stall as a sign that the plane was going too fast (an invalid representation) and moved to apply the speed brakes, another invalid contribution and completely inappropriate in the circumstances. Robert, who appeared to have a somewhat better grasp of the situation, immediately overruled him. Without realizing that they were doing so, and despite aural and visual warnings from the aircraft instruments ("dual input") Bonin and Robert repeatedly made simultaneous and contradictory inputs with their sidesticks, essentially cancelling out the actions of the other - "heedlessly interrelating" in Weick and Roberts' terms. At about 8,000ft and approximately 50 seconds before impact, Bonin declared that he had been commanding nose-up with his sidestick (see Table 3). This was the cue that finally allowed Dubois and Robert to achieve a valid representation of their plight. Robert attempted to put the nose down with a 15 second nose-down command on his sidestick, the appropriate stall-recovery action. But Bonin, perhaps not even aware of his own actions, continued to pull back on his sidestick. The FDR reveals that Bonin's side stick was in the full nose-up position at this time.

Table 3: CVR transcript approximately 50 seconds before impact

02:13:36	Robert	Climb, climb, climb, climb
	Bonin:	But I've been at maxi nose-up for a while
	Aircraft:	Dual input
	Dubois	No, no, no, don't climb

By then there was insufficient time and altitude to avert the crash. The official report concludes:

> "[Following] autopilot disconnection, the failure of the attempts to understand the situation and the de-structuring of crew cooperation fed on each other until the total loss of cognitive control of the situation" (BEA, 2012, p.199).

Discussion

AF447 illustrates the destructive dynamics that can be unleashed when a normally very safe system encounters an unusual, unexpected situation. The loss of AF447 demonstrates the challenges to individual and collective cognition – to mindful organizing and sensemaking - that arise when actors abruptly find themselves in a situation that is outside their experience in which they have only a limited amount of time to develop a representation of what is happening and respond to it.

The AF447 pilots had to more-or-less instantaneously adjust their roles from being 'system-monitors' to 'active controllers' and, within a very short time, diagnose and respond to a situation that they had never encountered before and of which they were unable to build a sufficiently valid representation. Here, the absence of experience at, or close, to normal limits was clearly a liability, particularly for Bonin. Aggravated by a strong startle effect, Bonin's excessive initial responses caused a relatively benign situation to spiral rapidly out-of-control. Unaware of Bonin's actions, his considerably more experienced colleagues were unable to decipher what was going on in time to recover the situation, perhaps because what was happening – a deep stall - was so implausible and so far outside their experience that they discounted it – recall Dubois' exclamation of "It's impossible". Throughout the whole episode an aural warning from the aircraft instruments called out 'stall' 75 times, yet none of three crew members acknowledged it or showed any signs that they had incorporated it into their individual, let alone collective, mental representations of what was happening to the aircraft until it was too late to recover.

Part of the problem was that the most serious limit violation, the excursion from the safe flight envelope, occurred very quickly and the cues that this was happening (such as the stall warning and buffet) were either missed, misinterpreted or ignored. The crew then found themselves in a world that was way beyond the limits of their experience and their "dynamic cognition" (Amalberti, 1998) failed. Or, to put it another way, their capacity for "mindful organizing" broke down in the face of the multiple challenges caused by prolonged operation with safe limits, an unfamiliar, unexpected event that was hard to represent and a rapidly escalating crisis that was caused partly by their own contributions to the situation.

AF447 is a vivid example of a LOC incident, a phenomenon that is causing widespread concern within the aviation community. Understanding the LOC problem in aviation therefore carries important lessons for other safety-critical sectors that face unusual events. In discussions of LOC, two themes are prominent, one concerning cockpit automation, the other concerning preparation for unusual, unexpected events, in particular issues around training and the authenticity of simulation-based training. We shall consider each in turn.

Cockpit Automation

Automation and fly-by-wire technologies contribute significantly to airline safety, almost all of the time, but by definition they also mean that pilots spend their time operating well within the safe flight envelope, unless for some reason, normal protections are withdrawn, as they were on AF447. Automated flying also means that for much of the time pilots act as system-monitors, depriving them of continuous, intense, hands-on experience in aircraft handling under varied conditions. Automation contributes enormously to safety by reducing scope for pilot error, but it also reduces opportunities for pilots to constantly refine, reinforce and update the cognition-action-response cycle. This may result in an erosion of the collective cognitive skills that are required when dealing with unusual events under difficult conditions (Learmount, 2011). In the language of mindful organizing, this represents a degradation of the "rich awareness of discriminatory detail and … capacity for action" identified by Weick and colleagues (Weick et al., 1999) , a degradation not only fostered by automation, but concealed by it. Most of the time, this is not an issue; nearly all flight crew are capable of flying and managing their aircraft under more or less all conceivable conditions. If they were not, accidents in commercial aviation would not be so infrequent. The problems arise in *inconceivable* conditions, such as those that played out on the flight deck of AF447.

One response by the aviation community has been to try to encourage the hands-on engagement which is normally limited by automation. For example, in 2013, the Federation Aviation Administration issued a safety directive that urged airlines to encourage hand flying, arguing that:

> "Autoflight systems are useful tools for pilots and have improved safety and workload management, and thus enable more precise operations. However, continuous use of autoflight systems could lead to degradation of the pilot's ability to quickly recover the aircraft from an undesired state" (FAA, 2013, p.1).

The argument here is *not* that flight deck automation poses risks under normal conditions. It is that automation, by reducing the need for constant direct interaction between pilots and their aircraft, subtly erodes pilots' ability to deal with very rare but extreme situations. We suggest that this erosion occurs partly through a diminished capacity for mindful organizing. As anomalies and opportunities for error are designed out of a system, operators experience fewer of them, will have a narrower repertoire of experience on which to draw and are less likely to have the capacity for the recognition-primed decision-making that is crucial in crises (Klein, 2017). Thus, as a stream of events develop into a crisis, flight crew are more likely to struggle to classify and interpret what is going on (which is the starting point for both collective problem-solving and procedurally-based responses) or have a sufficiently broad, shared repertoire of experience and actions from which to select coordinated responses. The crew of AF447 appear to have suffered from exactly this problem. However, engendering this broader experience is neither costless nor straightforward, as we discuss below.

Training for Unexpected

Finding safe, cost-effective, methods to expose commercial pilots to the full repertoire of possible aircraft attitudes and behavior is a challenge. The AF447 accident report concluded that:

> “Current training practices do not fill the gap left by the non-existence of manual flying at high altitude, or the lack of experience on conventional aeroplanes. Furthermore, they limit the pilots’ abilities to acquire or maintain basic airmanship skills” (BEA, 2012, p.185).

Some commentators see this problem not just as a consequence of greater automation, but also of the way in which commercial aviation has expanded and developed over the years. In the early years of commercial aviation, most commercial pilots initially trained as military aviators, which involved handling aircraft in all attitudes, including aerobatics and other extreme manoeuvres. The huge expansion of commercial aviation in recent decades has meant that very few commercial pilots now come through this route and proficiency in such manoeuvres is no longer required for civilian licenses (Brooks, 2010). Exposure to extreme aircraft attitudes provides experience and awareness that manifests itself in several ways: a greater ability to recognize what is happening by virtue of a broader repertoire of experience; practice at rapid responses; and, importantly, exposure to the emotional responses to unusual events that comes from real experience. The AF447 accident report alludes to the significance of such training, observing that “The exercises conducted by the French air force when they train pilots to work under stress currently appear to set the standard in this field” (BEA, 2012, p.156).

The challenge lies in accurately reproducing the full range of conditions that pilots might face in real life in a safe training environment. This challenge has both technical and social-psychological dimensions. From a technical perspective, the AF447 accident report questions the fidelity with which flight simulators were able to replicate the situation faced by the AF447 pilots. Although flight simulators simulate the *onset* of stall, the data package in use at the time was based only on information from *within* the flight envelope, because no data from real stall situations existed. The simulator therefore had no valid data on which to base a simulation past the point at which the stall had occurred. This is consistent with the pre-occupation of training with avoiding, recognizing and escaping from the approach to stall, rather than recovering from a stall that has already developed. Indeed, the Flight Crew Training Manual of the time remarks that “the existence of protections makes training in unusual attitude recovery training superfluous” (BEA, 2012, p.153).

Part of the issue here is a technical one of creating representations of a situation on which there is little or no real data, and in the view of some, near-zero probability of occurrence. But it is also about mimicking the full range of sensations likely to be experienced by pilots during an aircraft upset:

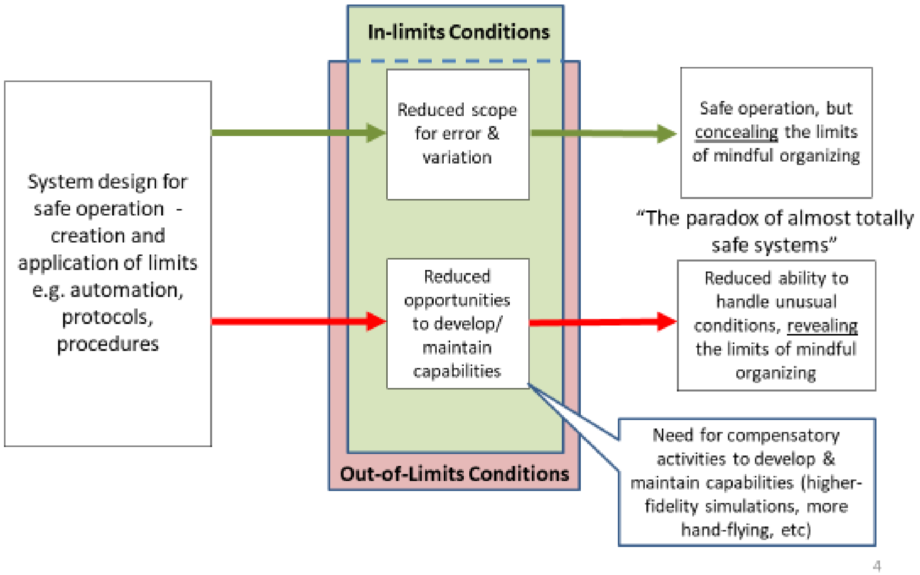
> “The development and acquisition of skills related to correctly and appropriately responding to the psycho/physiological reactions inherent in confronting undesirable aircraft states is fundamental to executing a safe recovery from an unexpected aircraft upset. The required learning cannot be achieved absent from the consequences faced in actual flight” (Brooks, 2010, p.8).

The AF447 report highlights similar issues in relation to the much less serious event of unreliable airspeed indications, which was the trigger to the sequence of events that led to the AF447 disaster. Air France used a simulator-based exercise for this scenario, which all three AF447 pilots had been through in the months leading up to the accident. (Bonin had actually undertaken the unreliable airspeed exercise just four months prior to the accident). However, such exercises are limited in its ability to reproduce the aforementioned psycho-physiological conditions: “The startle effect is difficult to create and/or maintain. The scenarios soon become known to the trainees, giving them the opportunity to prepare for the failures in advance” (BEA, 2012, p.155).

AF447 thus demonstrates the interplay between cognitive and psycho-physiological processes when actors must interpret and respond to expected, extreme situations (Maitlis and Christianson, 2014, Weick et al., 2005). Such situations test actors’ sensemaking and response capabilities to the limit. They may invoke emotional reactions that curtail heedful interrelating, due to startle effects, threat-rigidity, reduced efficacy of communication, all of which undermine mindful organizing, just when it is needed most. Preparation for such extremes thus requires the simulation of conditions that not only test and develop the diagnostic and cognitive skills of crews, but that are also sufficiently realistic to generate the psycho-physiological reactions that interfere with cognition, communication and coordination. Essentially, the challenge is to induce authentic, out-of-limit conditions whilst remaining *within* safe limits - an inherent paradox.

We represent these ideas in Figure 2. At the heart of Figure 2 lie two ‘circuits’ of causation, both of which follow from system designs in which limits regulate workloads and/or actor behavior in order to keep a system operating safely.

Figure 2: Limits, Safety and Mindful Organizing



Automation and system designs that minimize the scope for errors can produce remarkably safe operation, most of the time. However, by their very nature such designs also reduce direct engagement between complex systems and the crews responsible for monitoring and controlling them. They are also likely to restrict the variety of situations to which actors are exposed, limiting opportunities to develop broad action-repertoires. All of this has consequences for the capability to organize mindfully. To make things worse, this erosion of capabilities may be concealed by the very protections that limits provide, only to be abruptly revealed in rare combinations of conditions. Thus, the very same organizational attributes that yield safe operation in in-limits conditions may increase the risk of catastrophe when out-of-limits conditions are encountered. It is these conditions, we suggest, that produce a pattern of remarkably safe operation most of the time, interspersed with occasional, infrequent disasters. These, essentially, are the dynamics of an almost totally safe system (Amalberti, 2001, Amalberti, 1998, Reason, 2000). They highlight the limitations of a safety model in which humans perform the role of ultimate backstop when technology fails or when situations for which there is no established procedure are encountered. This model assumes that humans' ability to perform this backstop role is independent of the normal safety levels of the system; our analysis suggests that it is not, and that a subtle degradation in capacity for mindful organizing may occur in very safe systems.

If this theory is correct, responding to failures by imposing more stringent limits - either through automation or other means - risks further degradation of the capacity for mindful organizing and disturbance-handling on the part of the actors involved, *unless active measures are taken to counteract this*. Identifying strategies that allow errors to be designed out of a system without degrading the capacity for mindful organizing is therefore a key practical and theoretical challenge. One way to address this is through the development of better, more valid ways of creating out-of-limits conditions in simulated training environments. The AF447 accident report places considerable emphasis on how the limitations of simulator-based training may have played a role in the disaster; improving the scope and fidelity of simulations clearly has an important part to play in averting further tragedies. In this respect, the message of this paper is consistent with observations from the field of resilience engineering, namely, that attention must be given to how humans deal with complexity under pressure (Woods and Hollnagel, 2006), including developing their capacity to cope with complexity and uncertainty. Research into high-fidelity simulations, particularly in the field of health care, holds promise in this respect (Christianson, 2019, D'Souza et al., 2017).

Even so, we remain somewhat skeptical that accidents can be completely "trained" out of complex systems, simply because this assumes that it is possible to anticipate all contingencies, at least to a close enough approximation, develop appropriate procedures, train operators in these, and then rely on operators to recognize the situation and invoke the right procedure under any and all psycho-physiological conditions:

> "Initial and recurrent training as delivered today do not promote and test the capacity to react to the unexpected. Indeed, the exercises are repetitive, well known to crews and do not enable skills in resource management to be tested outside of this context. All of the effort invested in anticipation and predetermination of procedural responses does not exclude the possibility of situations with a "fundamental surprise" for which the current system does not generate the indispensable capacity to react" (BEA, 2012, p.209).

All three AF447 pilots had performed loss-of-airspeed exercises in the simulator in the months prior to the accident, but in heat of the moment none were able to evoke the appropriate procedure. There is also the risk that in some circumstances the prescribed procedure itself may be flawed. At the time of writing, this appears to be the case with Ethiopian flight 302 which crashed in March 2019, the second fatal crash of a Boeing 737MAX within five months. A system designed to automatically provide nose-down trim actions under certain conditions malfunctioned. Preliminary analysis suggests that the Ethiopian pilots initially followed the procedure advocated by Boeing but this did not enable them to recover the aircraft (Gates, 2019).

The implication is that it is not necessarily even more training in even more known scenarios that is required, but rather training that develops the general skills and capabilities to deal with unspecified, as yet unknown, scenarios that will inevitably occur in the future. Precisely what form such training should take is an important question for the safety science community.

Conclusions

In this paper we have sought to bring together concepts of mindful organizing, automation and organizational limits to explore the paradox of almost totally safe systems in general, and the problem of LOC in particular. This highlights the significance to mindful organizing of both experiences close to, or outside of, normal limits and constant, close engagement between actors and the systems that they manage (Amalberti, 1998, Amalberti, 2001, Farjoun and Starbuck, 2007, Rochlin, 1997).

Our analysis has focused very much on the collective responses of actors ‘in-the-moment’ when faced with an unusual, unexpected event and on the challenges in developing and maintaining the capacity to respond to such events. In doing so, we have not delved into the more general contextual conditions that may facilitate and impede mindful organizing, such as culture or leadership. However, the potential significance of these issues has been recognized (Bierly and Spender, 1995, Weick, 1987, Weick, 1990, Weick and Sutcliffe, 2015) and further research could usefully investigate the backcloth against which in-the-moment responses are played out.

Future research could also develop and test the model we have presented here, which we hope offers a way to move beyond simple descriptions of failures of mindful organizing and sensemaking to an understanding of *how these capacities can be developed*. The concept of organizational limits has considerable potential in this regard. Studies that examine how limit violations are induced or simulated in order to (safely) encourage the development of mindful organizing and sensemaking capacity may prove particularly useful.

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