FLIGHT SAFETY FOUNDATION

LEARNING FROM ALL OPERATIONS INITIATIVE

Foundational Support Document

How Operators Can Create Safety in an Uncertain World

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Executive Summary

This document examines the evolving understanding of *complex adaptive systems* in which we accept that uncertainty is part of everyday operations. Aviation, with its socio-technical nature, is an example of such a system. Furthermore, we explore *adaptive capacity*, which is the foremost capability that has helped us achieve high reliability despite the challenges brought by complex operations.

First, we describe a historical view of the world as a machine that exists as an ordered system. We then explore why this view of the world will no longer apply, given that today's systems are only predictable to a certain extent — with complexity breeding further complexity, an ordered view of the world is only partly useful. We emphasise why humans need to be acknowledged at the heart of today's complex adaptive systems, mainly because they are the only real-time agents that can adapt to surprises and unexpected situations.

Following that, we examine today's complex adaptive systems through the lens of information flow as outlined by Norbert Wiener, an American scientist who studied communication between humans and computers in the 1940s. We give examples that describe interdependencies within the aviation system and how frontline operators use their adaptive capacity to overcome the inherent complexity, both in rare but high-impact events and in more frequent but less severe scenarios experienced during everyday operations. To support our assertions, we have included a basic overview of complexity.

We conclude that it is time to move beyond the ordered system understanding towards an understanding of the aviation system as a complex adaptive system which contains surprises and unexpected events that need adaptations every day and also in rare, high-risk events.

By the end of this document, we hope you will find the concepts engaging enough to consider further reading. Armed with this paradigm, we suggest starting with the Flight Safety Foundation paper on Learning From All Operations.

From the outset, it is essential to clarify that we do not advocate this to be a wholesale change in the safety management approach, but a move towards more support for adaptive capacity.

1. The World as a Machine

Through such luminaries as Newton, Descartes, and Laplace, many people have come to view our world as a giant machine that can be described by the sum of its parts. This is a standard view of system management and the world — in other words, an ordered system approach of 'world as a machine' in design and operation. It leads us to believe our systems can be broken down into constituent parts, improved and managed in isolation, to achieve the desired output.

Humans are drawn to predictability, and an ordered system view offers an almost irresistible draw of potential predictability and, consequently, perfectibility. This search for predictability and order leads us to believe that unpredictability in outcomes and operation is always an indicator of system design problems or incorrect operation by the workers. This perception of system design reinforces the concept that we can drive out unwanted outcomes by process design and compliance alone.

2. Beyond the Ordered System

But what if the systems we try to control are not as predictable as we think?

- What if parts of the system are inherently unpredictable and produce situations in which we must compensate and adapt for the unpredictability?
- What would cause this, and what do we do then?

In a world beyond ordered systems, there is a need to understand the complexity involved. We define complexity as: a system in which the parts are interconnected and interdependent, creating a whole greater than the sum of its parts. This view, which acknowledges emergent outcomes and uncertainty, gives us an improved mental model in which system operations have further dimensions.

This is a world in which complexity breeds complexity (Kauffman, 2019). Each system variation, planned or circumstantial, generates new areas for further context changes, filling the gaps in context with different processes and, so, different outcomes. New system outputs emerge unseen and unknown and create uncertainty that must be controlled or predicted. This is the foundation of evolutionary theory. Consequently, managing systems through control and perfectibility will only ever be effective in the ordered parts and most likely very damaging to the complex parts, if not monitored and controlled.

As an example of complexity breeding complexity, we can see that as internet browsers became mainstream, opportunities opened for applications, or apps, to support them, such as ad blockers, password saving apps and more. In much the same way, as our aviation systems become more complex, different processes and outcomes occur, planned or unplanned. This happens on both the macro and micro scale, with or without our intervention, and on timescales from the very short to the very long.

Luckily, some wise people, Wiener (Wiener, 1948), Hollnagel, Leveson and Woods (Hollnagel and Woods, 2006), to name a few, have looked at what happens in complex adaptive systems, such as the aviation system. They have developed a different systems view using complexity theory. This view is being adopted worldwide and in many fields of work, giving us new approaches to building safer operations. The foundation and focus for this paper are to encourage and support safety management and a move into the approaches that support and value the understanding of the complexity that exists in the world and our aviation systems.

It is also worth noting that although this complexity causes a dangerous level of uncertainty, it also makes our systems resilient to significant consequences. It is not an option to drive complexity from the system in the hope of achieving predictability and stability. You will already be aware of this if you try to imagine what might happen if you replaced the humans in your system with the computers available today (see examples below).

The acknowledgement of complexity or 'uncertainty' generates two fundamental tenets of safety for complex adaptive systems.

- We must learn in the live environment to maintain an understanding of how our system operates in reality. Only by doing this will we have the options to manage and support safe operations in the most effective way.
- We must support and help create adaptive capacity within the system to manage the natural variability. The primary source of adaptive capacity is that of the humans within our system. They are the glue that holds system operations together in an uncertain environment.

3. The Human: The Only Real-Time Agent

We often hear that human error or actions cause 70 to 90 percent of all accidents. The technology that worked as specified is another frequently used phrase to focus on unreliable humans. A response to this thinking is often to ask for more technology or more adherence to rules to control the 'unreliable humans', which means the human operator of the technology in almost all situations. As mentioned before, if this claim is valid, why do we not substitute the human with a computer?

Woods and Hollnagel define resilience as:

> *"The intrinsic ability of a system to adjust its functioning before, during, or after changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions."* (Woods and Hollnagel, 2006)

Safety management expert Mario Pierobon says that if there was ever an industry that has demonstrated this ability, it is the aviation industry. The industry has continually shown the ability to adjust and sustain operations during and after unexpected events (Pierobon, 2021).

Woods and Hollnagel emphasise that we need to function both under expected (ordered) and unexpected (complex) conditions. So, what are these expected and unexpected conditions, and how did we organise our system to respond to emergence and change? The unexpected events can, of course, be prominent cases like 'QF32' (Qantas Flight 32, 2010) and the Hudson River landing of US Airways Flight 1549 (2009). But they also can be the everyday adjustments that operators must perform — for example:

- Technical limitations that require workarounds;
- Changing weather conditions;
- Communication problems;
- Different cultures that make people respond in multiple ways;
- Changing management priorities; and,
- New procedures that change actors' behaviours (e.g., when International Civil Aviation Organization (ICAO), European Union Aviation Safety Agency or local rules change).

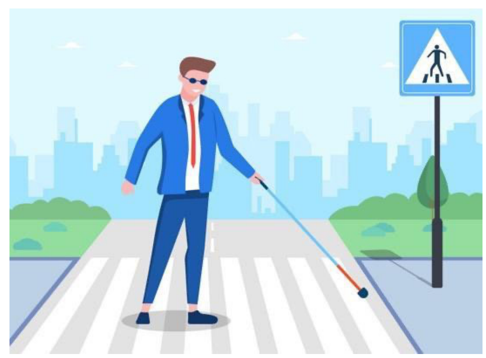
Operators and system managers adapt to these everyday variabilities through learning from experience, training, implementation of technology, availability of adequate resources, well-organised airspace, and many other means. All stakeholders shape the system's ability to adapt to the variability both in expected and unexpected situations, and the operators are the real-time adaptive agents of the system (Paries, Amalberti, 2000).

Aviation stakeholders have built a highly reliable system over decades, and it has been a team effort. We need to remind ourselves about the positive results we have achieved and recognise that when we fail, which is very rare, it is also teamwork, not individuals, that fail, or maybe a natural evolution of the system that creates an undesired outcome.

4. Interdependencies and Adaptive Capacity — The Flow of Information

To support the above view of complex adaptive systems, the following analogy has been used for decades to understand the interdependencies that are part of the web of complex systems and to support our understanding of why so many things go right every day.

The Visually Impaired and Their Canes



In the late 1940s, the developers behind the theory of cybernetics and especially Norbert Wiener (Wiener, 1948), started to study the boundaries of the human in relation to the flow of internal information. Wiener asked whether the boundaries of the human are innate or constructed. In 1972, Gregory Bateson, based on Wiener's ideas, asked: "Is a visually impaired person's cane part of him?" and "Is a deaf person's hearing aid part of him?" If we take the view that the boundaries of the human are innate, then the answer to both questions would be that neither the cane nor the hearing aid is part of the human. On the other hand, if we take the constructed view and we want to understand the flow of information, it is more difficult to define the limits of the process and the limits of the human. The cane and the hearing aid are part of the process, and it becomes difficult to determine the boundaries of the process.

If we look at the flow of information in the two examples, the boundary of the process is infinite. The cane is an enhancement of the visually impaired person's functionality. In today's society, the pavement designers and the workers who build the pavement enhance and influence the visually impaired person's functionality. Taking this thought further, sounds from traffic lights, noise from cars, braille on surfaces, etc., enhance the possibilities for the visually impaired person to process information and navigate everyday life. Engineers, workers, designers, rule-makers and more are included in shaping the conditions for the flow of information about the environment that makes it possible for visually impaired individuals to find their way. From a wider perspective, the economy is also part of the equation. A society with a surplus of finances is better positioned to support the process and build the infrastructure than a less fortunate society. Another factor that could influence the flow of information is the weather.

Similarly, the aviation system is a web of operators, designers, technology, rule-makers, financial trade-offs, weather and probably many more stakeholders and factors that influence the conditions under which information flows within the system. Since the Convention on

International Civil Aviation, known as the Chicago Convention, (ICAO, 1944) was signed in 1944, we have spent more than 70 years organising the global aviation system. We have made millions of trade-offs, developed a large number of procedures, implemented technological systems, designed airspace, discussed issues and trained to deliver the highly reliable service that the aviation system provides every day. But we have only been able to do this because of our ability to think beyond the boundaries of the individual. This ability needs to be enhanced, and we need to conserve the skills and the thinking demonstrated in the example of the visually impaired person.

5. Air Traffic Control and Pilot Examples

Below, we give examples demonstrating system dependencies and the constraints under which pilots or air traffic controllers work and adjust their everyday actions. The purpose is to show how a system and team effort are aimed at creating a safe, efficient and adaptive aviation system. None of the examples pretends to describe the dependencies and the necessary adaptive capacity in their entirety. Instead, the examples are designed to provide the reader with a flavour of the infinite number of dependencies and adaptations involved every day in expected and unexpected situations.

Example 1: Implementation of a Situation Display in an ATC Unit

In the initial design phase of a situation display and technological support system used by air traffic control officers (ATCOs) to control traffic, designers need to make trade-offs between costs, safety, capacity, rules and regulations, global plans for aviation, and the environment.

- **The Interdependencies**
  One example of interdependencies that shape the conditions under which the operators are working was to let a calculated flight profile for each aircraft type determine the sectors where the flight is presented to the ATCOs on their situation displays. However, this decision leads to rare situations where aircraft are not presented to ATCOs on the sectors that can be impacted if the flight performs differently than the calculated profile. In turn, this creates situations where it can be cumbersome to offer the most efficient flight path to aircraft. Design decisions thus influence trade-offs between costs, safety, capacity, and environmental aspects of everyday work years later. Of course, the designers' decision was also influenced by the same outside factors and shaped their world and required trade-offs.
- **The Adaptive Capacity**
  To provide the best service and a safe and efficient flight, ATCOs use several strategies to overcome the limitations of the technology to provide continuous climb and a smooth flight for the aircraft involved. ATCOs develop skills to recognise different aircraft types where the computer tends to make the calculation that leads to the missing presentations on the relevant sectors. One way that ATCOs can adapt to this situation is by making a manual input to the requested flight level, which triggers the information to be sent to the next sector. Following that input, it is possible to contact the next sector and coordinate the change to the system preplanning. This happens within seconds and at times when the ATCOs have developed their strategies; this effort may require limited resources in everyday work, yet these workarounds go almost unnoticed.

Example 2: Making CPDLC work

CPDLC (Controller Pilot Data Link Communication) is the two-way data-link system by which controllers can transmit non-urgent strategic messages to an aircraft as an alternative to voice communications.

- **The Interdependencies**

  The CPDLC concept was introduced after years of preparation. The stakeholders involved were ICAO, Eurocontrol, the U.S. Federal Aviation Administration, EASA, the International Air Transport Association, the Civil Air Navigation Services Organisation, staff associations, the industry, and many others. They all participated in developing the technology needed, the requirements for making the technology work, the training programmes and the rules that surround the concept. Today, CPDLC works but is suboptimal in terms of both capacity and an operator's point of view. It was a cumbersome process that finally introduced the tool around 2010. The process included many trade-offs, mostly between cost and useability. The stakeholders shaped the conditions under which operators work and the adaptations that operators need to perform to make it work.

- **The Adaptive Capacity — Air Traffic Controllers**

  ATCOs use CPDLC mainly to reduce voice communication with pilots. But there are problems. First, communication breakdowns occur in 10 to 15 percent of CPDLC messages, which leads to CPDLC being used as a support tool. In many situations, the use of CPDLC functionalities is reduced to frequency change.

  Another obstacle to the user is the short flying time in a sector. To reduce the workload for pilots when an aircraft is flying a short distance in an ATC sector, the ATCOs would like to transfer the aircraft not to next sector but to the sector after that [essentially skipping over one sector]. This action requires some adaptation because it can lead to confusion. ATCOs then develop strategies to cope, depending on how the technical system works and how their colleagues work. Again, many stakeholders and conditions shape the operator's work, which leads to everyday operator adaptations and shows how it is a team effort to make CPDLC benefit the overall system.

- **The Adaptive Capacity — Pilots**

  Pilots use CPDLC mainly to reduce voice communication with ATCOs, but one obstacle to greater and more valuable use is the basic level of information the system can transmit. As with all complex environments, context is essential, and CPDLC can handle very little, restricting its use to the most basic tasks. If there are no immediate other paths to follow, pilots adapt to CPDLC by reverting to voice communications.

Example 3: Auto-Thrust

This is standard on most modern jet airliners and is a tool to reduce pilot workload by automatically controlling the aircraft's energy state. On some aircraft, the auto-thrust system maintains airspeed, and in some instances, it maintains the aircraft's energy state through engine thrust control. It reduces the workload for pilots, especially during high workload situations, but still has limitations in the live environment that the pilots must work around.

- **The Interdependencies**

  There are obvious interdependencies between regulators, airline policy designers and pilots in the use of auto-thrust for everyday operations. One such interdependence is the need of some airlines to enforce auto-thrust use at all times except in case of system failure. In doing so, they take the view that the short-term risk they perceive to be created by pilots not using the auto-thrust and making mistakes outweighs the long-term risk created in situations when pilots are forced to fly without auto-thrust because of system failures but are unable to do so due to lack of practice. There may also be considerations for fuel and descent management, thrust changes and noise regulations.

- **The Adaptive Capacity**

  The adaptive capacities needed by the pilot using and not using the auto-thrust include the pitching moment of the aircraft engines during thrust changes, wind speed changes for aircraft angle of attack based on configuration and drag characteristics, energy management considerations and more.

  In very gusty conditions, the lack of intuitive feel for the handling of the aircraft by the system can lead to a destabilising effect on the flight path. So, pilots may well choose to operate without the system under these conditions. Auto-thrust use is not allowed under specific unusual landing configurations following aircraft system failures due to the system's adaptation limitations.

  Pilots also have a complete contextual understanding of the live environment, which gives them an advantage over automation when anticipating changes in atmospheric conditions such as gust fronts from storm clouds, temperature inversions causing sharp wind changes, warnings from other pilots and expected engine performance from recent experience.

Example 4: Flight Path in Descent

All modern jet airliners have some kind of flight management computer that generates an aircraft descent profile to aid the pilot in managing the aircraft from high altitude to airfield. This will factor in the wind, aircraft weight, deceleration, and aircraft configuration profiles.

- **The Interdependencies**

  The flight management profile in descent, as with auto-thrust, has many interdependencies among regulators, airline policy designers and pilots. For example, regulators need to balance air traffic management needs while trying to improve fuel burn and noise creation, which are both descent profile–dependent. At the same time, the airline policy designers are also keen on fuel usage from a commercial standpoint. These aims are interdependent with the other goals created by the live environment that the pilot has to contend with, such as possible descent angle changes needed due to weather considerations, turbulence and wind shear; time delays to landing; cabin state; pilot experience; and more.

- **The Adaptive Capacity**

  Each day, the pilot will plan a descent based on regulatory, commercial and environmental factors and will make a unique and informed decision, perhaps delaying descent to remain above turbulent clouds and then conducting a faster-than-normal descent or maintaining a higher speed to melt ice from the wings before landing in severe icing conditions. Or they may delay descent to save fuel if a delay is expected or change aircraft configuration at non-standard times to give better flight envelope margins due to expected turbulence or wind shear.

  The adaptations in this environment are myriad, context-dependent, and rarely in line with the flight management guidance computer on board the aircraft.

6. The First Step in Creating Solutions within Complexity

The first step is the most difficult: *changing our mental model of how the system operates*.

We should no longer see the aviation system as a machine to be made predictable, perfectible or fixable. In reality, we need to acknowledge that the systems we create have evolved to be beyond our direct control, even in small ways, and may occasionally result in undesired outputs.

In the context of Learning From All Operations, it is crucial to understand the interdependencies and the necessary adaptive capacities that make up our system. This helps us create consistent, safe operations by balancing the unavoidable conflicting goals of, at one end of the scale, being dependent on some level of 'work according to specified role' and at the other end, being dependent on operators' innovations in achieving system objectives that go beyond these role specifications (Kane, 1964).

We must understand that centrally made rules and designs shape the world of the operators for years to come, meaning that adaptation is necessary for achieving acceptable results as the environment changes around a fixed system designed for a world long since passed.

> *"No man ever steps in the same river twice, for it is not the same river and he is not the same man."* (Heraclitus)

This means our understanding of risk and context needs to be continually updated from the real world to adequately support real-time risk management, which predominantly sits with the frontline staff.

It becomes clear that the *first and most crucial step* in supporting solutions is *Learning From All Operations*. This means having a sufficient level of understanding of the live environment to make the necessary adjustments to maintain safe operations within uncertainty.

Questions that can help us develop the necessary capacity could be:

- Where do we need to add adaptive capacity or take it out and save resources?
- How does our system as a whole create context in culture, systems of work, and in the minds of our workers?
- What properties are emerging, and are they undesired or helpful?
- Where do workers need to adapt to keep the system on track?
- And how can we support this need rather than controlling it?
- What are workers asking for to keep them safe?
- Can we learn from and use these adaptations?
- Where might changing the system avoid the need for adaptation?
- Do other parts of the airline/air navigation service provider create an appropriate context for workers to succeed?
- Does our accident/incident response support and create the proper learning?
- Is our incident/accident investigation process tuned to understand context and complexity?
- Are we using an abductive approach to learning in the complex parts of our system?
- Where might our training better support this adaptation?
- Where is the workers' explicit and tacit knowledge of the system failing them and why, and is there an appropriate balance in the training/learning of explicit vs tacit knowledge?

7. Conclusion

An understanding of complexity, and the modern world, means we have to take a two-pronged approach to safety management.

The first prong we are already very good at: safety creation for the ordered environment. We have done this by ever-increasing levels of understanding of the system operation, making it more ordered. Improvements in safety as measured through accident and incident rates are now plateauing as we find there are limitations to this approach and so now is the time to add a second prong.

The second prong should start with a basic understanding of complex adaptive systems theory. Due to the pace of change and complexity within our operations, we should start to think differently about how we create safety within the complex, and unpredictable, areas of the operation.

This acceptance of built-in uncertainty as an addition to current safety theory should be fostered within our organisations. Learning should be at the core to support all available sources of adaptations within the system. To reiterate, a good first step here would be a reading of Flight Safety Foundation's Learning From All Operations literature.

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