FLIGHT SAFETY FOUNDATION

LEARNING FROM ALL OPERATIONS

Concept Note 4

Patterns of Operational Resilience

APRIL 2022

FLIGHT SAFETY FOUNDATION

A note to the reader:

The goal of these Concept Notes is to provide a common framework and common language for talking about aviation safety. Such a new framework and language are needed because the existing language of safety is built around learning from failures and cannot easily express learning from success. Similarly, the existing frameworks of safety data collection and analysis are designed for incidents and accidents, and we want to learn from all operations.

As we expand our understanding of what constitutes a safety-relevant occurrence — an expansion that encompasses learning from all operations — we need a shared means of articulating what we are already learning that also allows discussion of new ways of learning. Positing a separate framework for describing safety successes, however, can create challenges for relating what can be learned from success to what has been learned from failure. Therefore, the goal is to describe a unitary framework for safety based on learning from all that happens, rather than separate frameworks for different "kinds" of safety. To achieve this goal, each of these concept notes establishes part of the necessary foundation which is then integrated and translated into practical implications and applications in Concept Note 7.

1. Introduction

This note introduces the second important learning dimension of Learning From All Operations. It is about monitoring aviation operations and **learning from the different patterns of operational resilience.** As described in this note, operational resilience is present all the time and can manifest in different ways. Pressures are always present in operations and they are followed by system adaptation. The adaptation can further secure the system state in the prevention space or it may result in the system transitioning to a hazardous state or even beyond the safety envelope (see Figure 1). In all the cases, there is something useful that can be learnt.

2. System critical and hazardous states

The safety envelopes described in Concept Note 3 draw the boundaries of our control on safety in operations. Similarly, Figure 1 illustrates the safety envelopes but also shows system operating point transitions in this performance space.

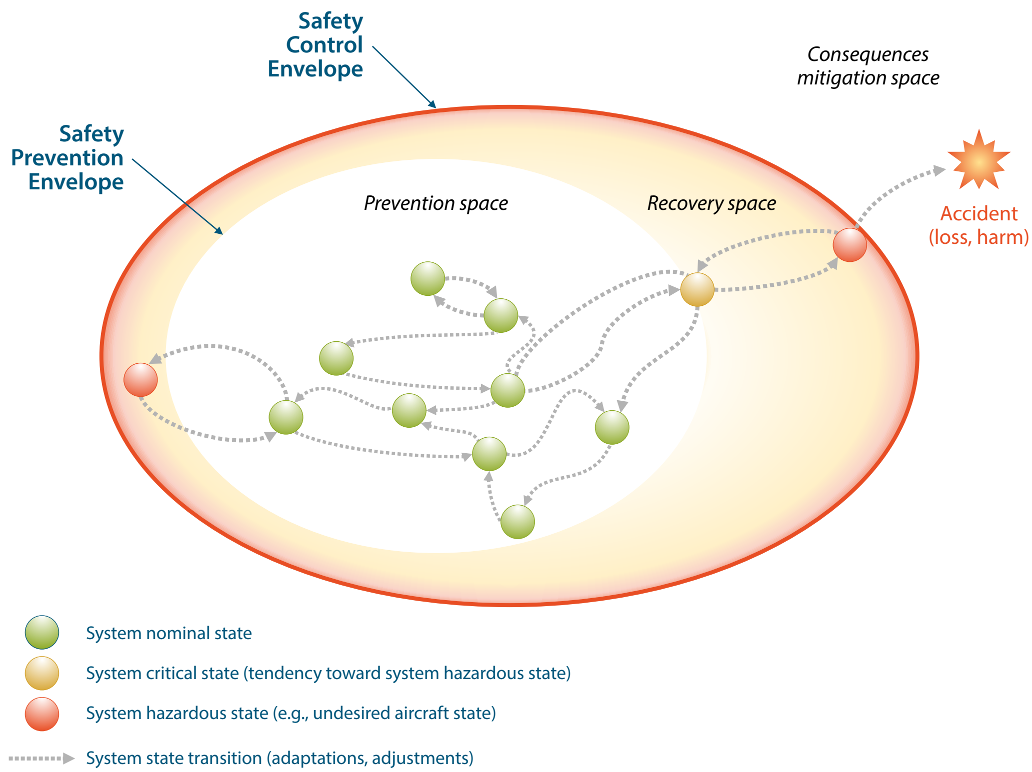


Figure 1: System States

The states that are illustrated in green are in the prevention (white) space. The system operating point transitions back and forth, pressures appear, followed by system adaptations typically intended to keep the system away from the safety prevention envelope boundary (the border with the yellow space). For example, the system state may represent the airspeed during approach. There may be fluctuations in the airspeed during approach that are still within the nominally expected range — illustrated by the transitions in green.

However, **it is possible that some pressure comes as a surprise or counter-pressure is not sufficient**. In this situation, the system operating point can transition to a critical (yellow) state (Fiksel, 2015) and even further to a system hazardous (red) state (Leveson, 2004; 2011). For the airspeed example, there are two basic scenarios — high airspeed and low airspeed. For example, at 1,000 ft, the high airspeed critical state may be airspeed higher than Vref + 20 kt (SKYbrary, Stabilised Approach). The system operating point can even transition to a hazardous (red) state — for example, airspeed higher than Vref + 35 kt. Similarly, for low airspeed, we can define critical state airspeed lower than Vref – 5 kt and for the respective hazardous state — airspeed lower than Vref – 10 kt.

The system hazardous states, in this example, are types of unstable approach. It is to be noted that, often, high airspeed instability is more frequent than low airspeed instability. Additionally, the parameters defining the safety envelope can be extended to include thrust (more specifically low thrust), pitch attitude, vertical speed, roll attitude, glide slope and localiser deviations, and flaps and landing gear configuration.

The system in a hazardous state can, together with a particular set of conditions, transition further and result in an accident. For the example of high airspeed used above, the situation may result in an aircraft runway excursion.

3. System resilience

When we look at Figure 1, a legitimate question is "where can we see the system resilience"? Is it a system recovery from critical or hazardous states? Is it a rebound back into the safety envelope after the system state is "pushed" away from it? Is it just the system staying in the prevention space or is it something else?

As Learning From All Operations advocates studying both failure and success, risk and resilience, it is important to define the characteristics of system resilience. In the literature, resilience as a term has many different definitions and interpretations (see Hosseini, Barker, & Ramirez-Marquez, 2016, for a review). Resilience is often cited in the context of crisis response, but its meaning goes deeper: the proactive building of skills and capabilities to sustain purposeful operations for the long term.

Learning From All Operations emphasises a **holistic and integral point of view**, in which learning takes place continuously from everyday situations — from successful adaptations to pressures as well as from incidents and accidents. It is natural, then, that use of the term resilience by Learning From All Operations is also holistic and is based on all possible events and situations.

In this way, the description of **resilience** used for Learning From All Operations from the safety point of view is focussed on the **different adaptive processes with the aim of sustaining purposeful operations under varying conditions and pressures, while maximising the likelihood of an accident-free outcome and minimising the undesired consequences of a potential or actual adverse event**.

Learning From All Operations uses the term ***operational resilience*** **to describe the system resilience manifestation in operations**. The use of "resilience manifestation" and not just "resilience" aims to highlight that these patterns are what we can observe in operations, what is measurable in terms of operational system behaviour rather than assuming that these patterns explain the underlying forces that interact to produce the observed system behaviour.

The Learning From All Operations conceptual framework connects the system adaptative processes, the pressures and contextual conditions that affect the adaptation, and the prevention of the system transitioning to an accident state. Using the metaphor of Figure 1, we will look for operational resilience in the following situations:

- When the system succeeds in remaining in the prevention (white) space;
- When the system succeeds in recovering from critical (yellow) and hazardous (red) states;
- When the system succeeds in rebounding back within the safety control envelope after previously transitioning out of it.

The above situations are seen at the system sharp end and in operations for which some typical patterns and examples of adaptation are provided in the next section. But moreover, Learning From All Operations advocates for looking not only at operational resilience but also at overall system resilience. This involves looking at the resilience potential and manifestation at different levels and time horizons, both at the operational sharp end and at the organisational blunt end as described in Concept Note 2.

When we holistically look at both the sharp end and blunt end, then the system adaptation and resilience manifestation can be seen even more widely:

- System changing its own state when under actual or anticipated pressures — operating point transitions;
- Reducing, eliminating or absorbing the pressures that are experienced by the system;
- Adaptation activities that occur during system design and redesign to modify safety boundaries — “expanding the space”; and,
- An interaction activity of learning about and contributing to the evolution of the system environment — mainly by the blunt end system but possibly by the sharp end (e.g., flight crew habitually not accepting late air traffic control (ATC) clearance changes).

In terms of operational resilience, the system blunt end can both enable or inhibit people’s resilient performance at the sharp end. The system blunt end is not only restricted to organisations like aircraft operators and air navigation service providers but also includes regulators, certification authorities, policymakers, governments, international organisations and society.

The system blunt end, including the organisations, can do a multitude of things at different levels to enable the potential for resilience at the sharp end and to sustain this potential over time. For instance, organisations can provide infrastructure and foster culture that nurtures the resilience potential and nurtures the capability for resilient performance by individuals, such as wide and deep learning and information sharing.

Resilient system behaviour is associated with different levels of surprise events. These events happen in such a way that may or may not provide time for reflection or the use of personal and team cooperative strategies to successfully manage them. These events can be:

- Expected and previously known events;
- Unexpected and previously known events, including situational and fundamental surprises; and,
- Unexpected and previously unknown events.

Learning From All Operations’ scope includes resilience potential to address both expected and unexpected, both known and unknown, risks.

4. Six patterns of operational resilience

It is possible to identify some typical patterns of operational resilience (Cook, 2005).

For example, we see an aircraft climbing very fast towards its cleared flight level; an air traffic controller, detecting that there is a potential for an altitude bust, repeats the previously issued clearance to the flight crew; the flight crew understanding that there was a potential confusion about the clearance, corrects the selected altitude; and the aircraft successfully captures the cleared flight level without clearance deviation.

This scenario is about operational resilience (the resilience manifestation); it is the visible part of the story. There are many other underlying layers of explanations that can describe the contributory and contextual factors at the system sharp end and the system blunt end — for example, understanding the adaptation process associated with the use of air-ground communication phraseology and procedures, the adaptation process of the flight crew interaction and cross-checks, or specific crew actions such as conducting debriefings and the sharing of lessons learnt.

It is useful to identify some patterns of resilience (Woods, 2015). In this concept note, we identify and provide examples of the following patterns of operational resilience:

- **Remaining within the prevention space—** prevent, avoid or withstand pressures to stay within the safety prevention envelope;
- **Recovering from critical state —** adapt to pressures and recover from critical state while preventing hazardous states;
- **Recovering from hazardous state —** recover from hazardous state, use and accept team intervention;
- **Rebounding back within the safety control envelope —** pass beyond the safety control envelope in a controlled safe manner; and,
- **Envelope expansion —** apply critical thinking regarding procedures and extend the safety envelopes, remaining open for change.

Below, we provide descriptions and examples of each of these five patterns of operational resilience.

4.1 Remaining within the preventions space

Remaining within the prevention space as a pattern of operational resilience can be seen as the system remaining within the prevention space — **by using system capacities (potentials) to absorb pressures and system capacities to adapt while remaining in the prevention space**. This pattern of operational resilience includes but is not restricted to system robustness. An important system capacity is not what happens after a surprise that affects the ability to recover but what capacities are present before the surprise that can be deployed or mobilised to deal with the surprise (Woods, 2015).

Let us use, as an example of remaining within the prevention space, the operational (sharp end) system "several flights to an airport with potential wind shear on final" (SKYbrary, Low Level Wind Shear). Even if not anticipated, the wind shear can be safely managed by adaptation based on training, procedures, experience and teamwork. When wind shear on final is not anticipated, there are still system capacities that can be deployed once the wind shear is experienced in flight. These system capacities can help ensure that the system remains in the prevention space. These capacities are based on individual and team competencies for wind shear recovery; correct and timely execution of a go-around if needed; and use of and following given aircraft-related wind shear recovery procedures. When the adaptation is successful, as illustrated in Figure 1, the system operating point transitions from a state of "nominal flight" to a state of

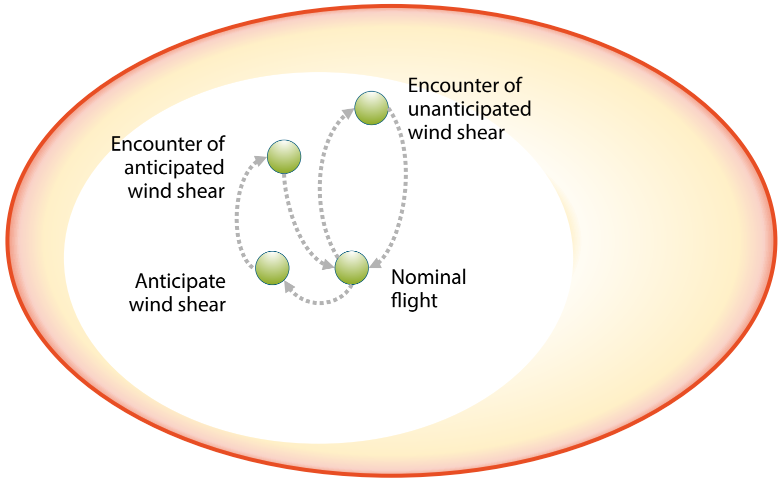


Figure 2: Remaining Within the Prevention Space Pattern of Operational Resilience by Operating Point Adaptation

"encounter of unanticipated wind shear". The system operating point gets closer to the safety prevention envelope (the boundary between white and yellow spaces), but the operating point stays within the prevention space.

Some situations of wind shear encounter on final approach can be anticipated. The anticipation may be based on previous experience at the airport or triggered by weather information received by the flight crew. The information can originate from wind shear detection systems, ATC or actual weather reports and weather forecasts. For example, the information may involve temperature inversion, the operational flight plan wind profile and its relation to the runway wind, information from a preceding aircraft, information from ATC based on preceding aircraft reports or information based on visible cues. Anticipating the pressures (wind shear on final) increases the likelihood of a successful adaptation and, in this situation, the resultant state of the operating point is "encounter of anticipated wind shear" — a point less close to the safety prevention envelope than the "encounter of unanticipated wind shear". In other words, anticipation helped provide a larger margin of safety.

Figure 3 illustrates another possible manifestation of the system remaining within the prevention space. This adaptive process is about **modifying and adhering to operational limits that**

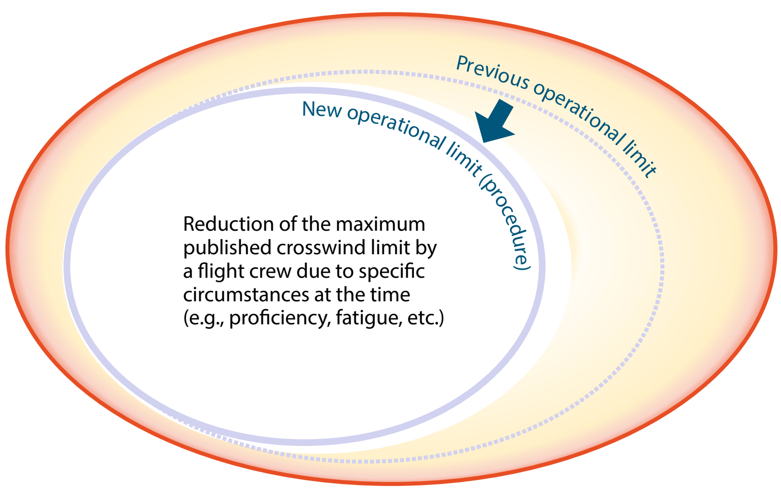
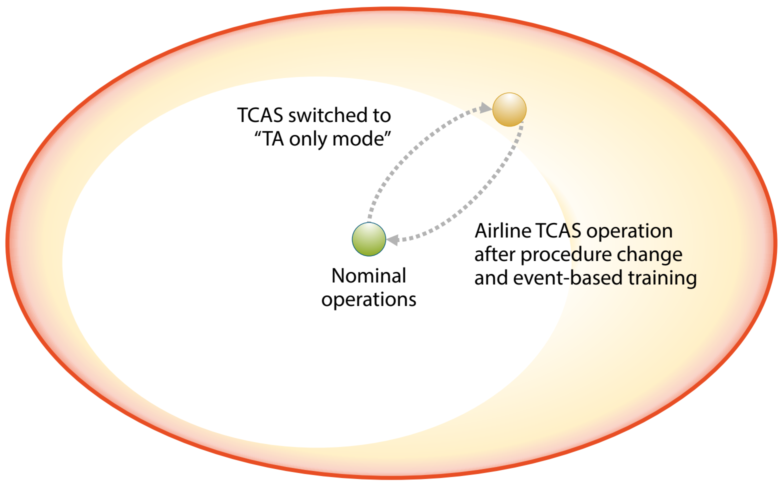


Figure 3: Remaining Within the Prevention Space Pattern of Operational Resilience by Modifying the Operational Limits

are more conservative than the nominal limits. An everyday example of this might be reducing the speed limit on a road when there is snow present. This is a specific pattern of remaining within the prevention space because it is achieved not by system states adaptation or by changing the safety envelope but by changing the operational limits (the procedures and practices used in the operations). An example might be a reduction of the maximum published crosswind limit by a flight crew due to specific circumstances (for example, proficiency, fatigue), which can contribute to reducing the risk of runway excursion (Flight Safety Foundation, EUROCONTROL, 2021).

4.2 Recovering from critical state

Recovering from critical state is a pattern of operational resilience that illustrates the system operating point transitioning through the safety prevention envelope to and back from a critical state. Here, for some time, the system becomes unstable in terms of safety control and then, the system recovers back to the prevention space (Figure 4).



TA = traffic advisory; TCAS = traffic-alert and collision avoidance system

Figure 4: Recovering From Critical State Pattern of Operational Resilience

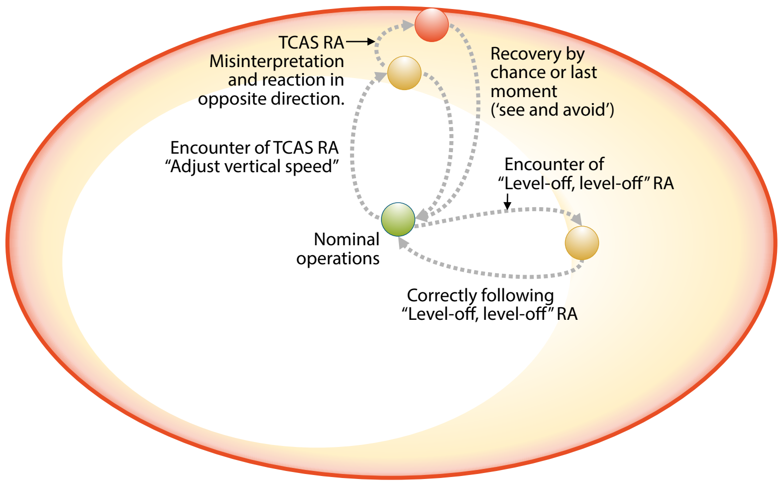
Recovering from critical state can be illustrated in airline operations with respect to traffic-alert and collision avoidance system (TCAS) operations during approach. All approaches are considered in this example and not just one specific approach to a particular airport. Here, the example is about the organisational (blunt end) system because it goes deeper than just examining the sharp end system of operations; it also includes organisational capabilities and processes. In the example, a practice observed in multiple events was that the flight crew did not follow a resolution advisory (RA) on final approach, assuming the threat was an aircraft on approach to a parallel, closely spaced runway. In these situations, the flight crew switched the TCAS to "TA [traffic advisory] only" mode to cancel the RA (SKYbrary, TCAS RA Survey). The observed repeated occurrence of this practice brings the operating point of the overall system of "airline operations" to transition through the safety prevention envelope and closer to the safety control envelope.

In practice, in the case of a legitimate conflicting aircraft, the TCAS would not provide an RA, and the situation would become hazardous. In other words, this situation is considered to be unstable in terms of safety control. For example, there will not be a TCAS RA provided for conflicting visual flight rules (VFR) aircraft infringing on the control area or traffic deviating from the final track of a parallel runway (e.g., while executing a go-around).

The airline identified the (undesired) adaptive transition to safety recovery space and adapted back through analysis of the events and the margins, and by introducing a procedure change for crews not to switch TCAS to ″TA only″ during approach. This adaptation also included event-based training in the simulator, based on the observed events.

4.3 Recovering from hazardous state

Recovering from hazardous state is a pattern of operational resilience that illustrates the system operating point transitioning through the system prevention envelope, via critical (yellow) states and to hazardous (red) states but recovering back to prevention (white) space.



RA = resolution advisory; TA = traffic advisory; TCAS = traffic-alert and collision avoidance system

Figure 5: Recovering From Hazardous State Pattern of Operational Resilience

An example of the recovering from hazardous state pattern of operational resilience is the aviation industry's response to the issues associated with the "adjust vertical speed" type of TCAS RA (Figure 5). The example includes the blunt-end system of aviation operations encountering unexpected crew behaviour in response to an "Adjust vertical speed" RA (SKYbrary, Wrong reaction to "Adjust Vertical Speed" RA). Here, the blunt end system is not restricted to just one organisation or one airline. The blunt end system includes regulators, certification authorities and the process of wide industry consultation and collaborative safety improvement.

In this example, a number of TCAS events have been observed in which the crew misinterpreted the RA. These events involved RA types "adjust vertical speed″ that were provided by version 7.0 of TCAS. The misinterpretation of the TACS RA resulted in the flight crew reacting opposite to the direction provided by the TCAS RA. In Figure 5, this is illustrated by the system operating point transitioning to the hazardous (red) state "TCAS RA misinterpretation and reaction in opposite direction" — a state of near-midair collision.

After some high-profile events, the aviation industry reacted to the identified risk. This led to a change in the technical specification through simplification of TCAS RA design and the introduction of TCAS version 7.1. In this version, the four types of TCAS RA "adjust vertical speed" were replaced by a single TCAS RA "level-off, level-off". A situation of two conflicting aircraft triggering a TCAS RA will still be a transition to a critical (yellow) system state "encounter of 'level-off, level-off' TCAS RA". But the likelihood of TCAS misinterpretation will be considerably reduced. Thus, the technical change influenced the resilience, because the probability for misinterpretation was lowered. For the observed sample of operations on which our example is based, there were no subsequent cases of misinterpretation of TCAS RA "level-off, level-off" and this is illustrated by no system transition to hazardous state.

4.4 Rebounding back within safety control envelope

Passing through the safety control envelope does not always result in an accident or fatality. Although it is undesired for a system to go through the safety control envelope, when it happens, it is still possible that adaptive capacity helps mitigates the consequences. **Rebounding back within safety control envelope** is a pattern of such operational resilience.

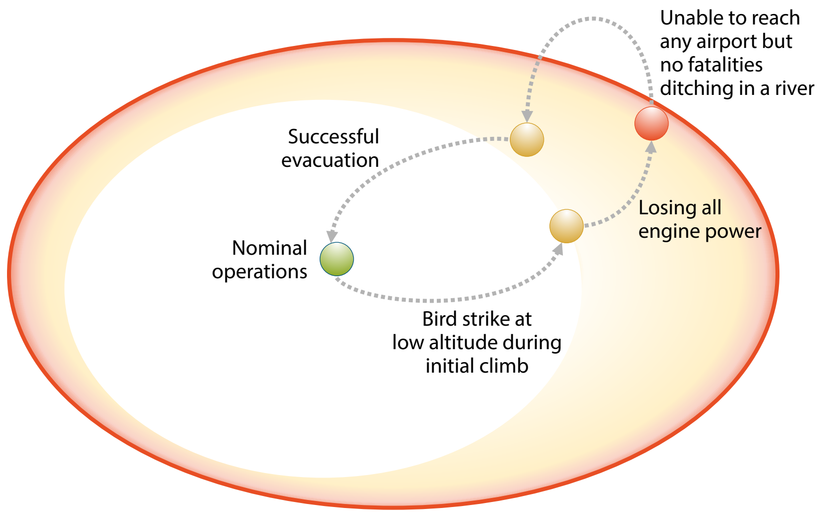


Figure 6: Rebounding Back Within Safety Control Envelope Pattern of Operational Resilience

In Figure 6, an example of graceful extensibility is provided for a sharp end system of operations involving a specific flight that suffered a bird strike at low altitude during initial climb. Following the loss of all engine power, the crew had several options — return to their departure airport, divert to a nearby airport or ditch in a river (SKYbrary, A320, vicinity LaGuardia New York USA, 2000). The flight crew rapidly assessed the situation: Engine conditions, altitude, airspeed and location. They determined that the aircraft had insufficient altitude and airspeed to divert, and that returning to their departure airport might not be possible and would entail flying over a heavily populated area. The crew decided the only workable solution was to ditch in the nearby river, which was successfully accomplished and was followed by a successful evacuation with no loss of life.

As seen in the example, the rebounding back within safety control envelope was influenced by flight crew adaptive behaviour and was not just because of luck.

4.5 Envelope expansion

Another key pattern of resilience manifestation involves expanding the performance space. Normally, this is a design-based adaptation activity to modify safety envelopes that takes place at the organisational or industry level and at a time distant from real-time operations. However, it is still possible that Learning From All Operations could identify envelope expansion patterns of resilience manifestation during operations.

An example of safety control envelope expansion in operations is illustrated in Figure 7 (p. 9). This example (Etherington, 2016) is about an operational (sharp end) system. After an unexpected rudder trim failure, there was a sudden loss of autopilot, and the aircraft immediately started to leave controlled flight. The flight crew had been provided with no procedure for such a situation, and there was only a generic checklist that covered all control problems.

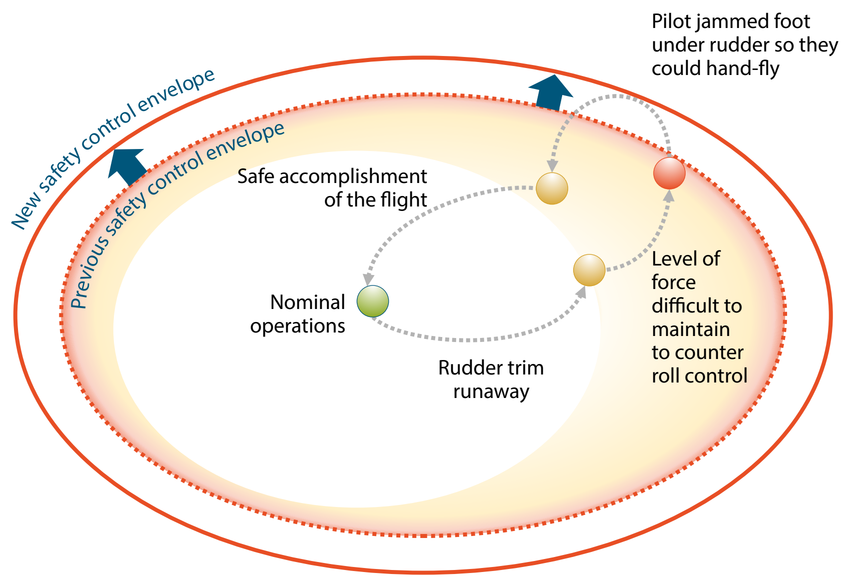


Figure 7: Envelope Expansion Pattern of Operational Resilience

For the pilot flying, it was difficult to cope and consistently maintain the level of force (about 40 lbs) to counter-roll control. After applying critical thinking, the flight crew came up with a solution — they jammed a foot under the rudder, so they could more easily counteract the force, and they could hand-fly without difficulty.

There is another possible pattern of envelope expansion which does not concern the safety control envelope but is about re-defining the safety prevention envelope. Expanding the safety prevention envelope is, of course, not sufficient to prevent the system state from transitioning to critical and hazardous states. But with all the other contextual conditions staying the same, the expansion of the non-critical performance space should provide more margin for system manoeuvres.

The example in Figure 8 illustrates a design activity of adaptation that results in enlarging the system prevention space — expanding the system prevention envelope. The example is about both safety prevention envelope expansion and sustained adaptability — both expanding the

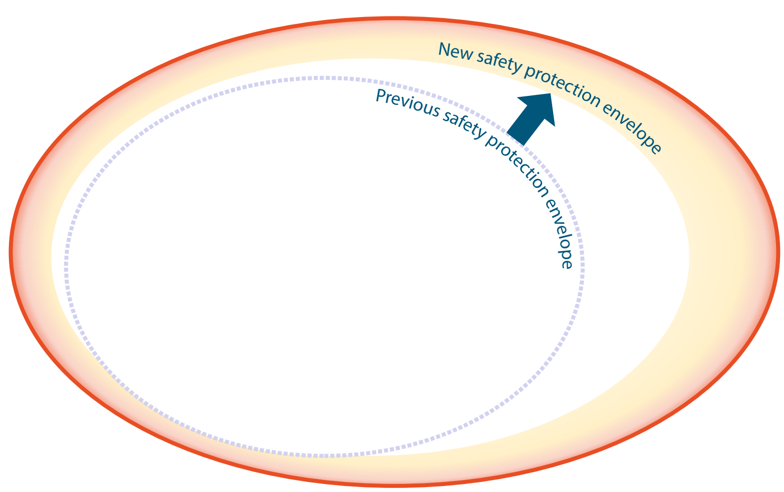


Figure 8: Prevention Space Expansion Pattern of Operational Resilience

white area and keeping the system in the white area. The safety prevention envelope was expanded after the introduction of full authority digital engine control (FADEC) technology (SKYbrary, Full Authority Digital Engine Control (FADEC)). This computer controls the engines and prevents engine stalls independently of the movement of the thrust levers. Previously, some engine stalls occurred on aircraft without FADEC (e.g., B727), whenever the movement of the thrust levers was too abrupt.

A similar example of both safety prevention envelope expansion and sustain adaptability (both expanding the white area and keeping the system in the white area) is about the implementation of tail strike prevention technology. This technology allows the flight crew to overcontrol the aircraft during takeoff rotation without a negative effect on safety, because the computer limits the outcome. The red line safety control envelope (measured as some distance from the runway surface) is not changed with the tail strike prevention technology. But the limitation technology will reduce the pitch-up command sent to the elevators in case of excessive pitch rate and reduce the risk of a tail strike. Transition to hazardous states is still possible because a tail strike event can still occur if a nose-up input is maintained.

By defining the patterns of operational resilience, this concept note provides another important learning dimension of Learning From All Operations. The patterns aim to help us identify behaviour in operations that is identifiable and measurable.

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