LEARNING FROM ALL OPERATIONS

Concept Note 2

Systems Approach

Flight Safety Foundation

MARCH 2022

1. Viewing Operations as a System

1.1 System form and function

The aviation environment is becoming more and more complex. In a complex environment, we ask more from the systems that operate in that environment and, as a result, the systems themselves often become complex as well (Sterman, 2002).

Learning in such a complex environment might not always be a straightforward exercise. To facilitate Learning From All Operations, it is useful to consider the collective, relevant aviation operations as a **system** (Ackoff, 1971). Aviation operations or any sub-part of them can be seen as dynamic systems with a defined boundary (International Civil Aviation Organization, 2018). This helps us to understand the operations' complexity (Kim, 1994). Learning From All Operations promotes understanding of and learning the system adaptations.

It is important to note that thinking of operations as a system is just an abstraction (Leveson, 2020) — it helps reduce the complexity by suppressing some of the contextual details, but these details may become important and should be reconsidered once a sufficient level of understanding is achieved.

Depending on what part of the operations we study, the system scope can be defined differently, for example:

- Flight crew functions during a particular time period — for example during taxi-out at an airport;
- A flight from beginning to the end;
- An approach at one airport;
- All take-offs of a given aircraft type during a one-month period; or,
- One air traffic control (ATC) sector's operations during morning traffic rush period.

What the system does is a system **function** (Ackoff, 1971). An example of an advanced surface movement guidance and control system (ASMGCS) function is "surveillance," which provides identification and accurate position information on aircraft, vehicles and obstacles within the designated area of an airport.

The systems thinking outlined herein is built on the International Civil Aviation Organization (ICAO) definition of system: "*An organized, purposeful structure that consists of interrelated and interdependent elements and components, and related policies, procedures and practices created to carry out a specific activity or solve a problem.*" (ICAO, 2018)

Operations are not a coherently designed system. Unlike equipment or procedures that are to be used for a specific situation, operations are at times complex systems that are not designed (Dekker, 2011). For example, when it is intended to learn from landing operations at a certain airport, this includes interaction of the system "aircraft" with the system "air traffic control" and the system "airport". Even if specific elements of these systems are well designed, for example, use of automatic landing in low visibility, operations may at times appear as complex systems. Operations take place, shaped by cultural diversity, hierarchical gradients, varying standards and regulatory frameworks and adaptations to respond to pressures that sometimes lie beyond specifications or procedures.

1.2 System boundaries and entities

As shown above, the **boundaries** of the system are relative to how exactly the system is defined (Leveson, 2011). When we study a system, it is extremely important to rigorously define the system boundaries. Identifying the system boundaries is an important exercise because it brings an explicit elaboration of:

- What is in the system and therefore, what is within the control of the respective project or initiative;
- What is outside the system and cannot be controlled but needs to be coordinated; and,
- What is to be considered as a context which cannot be coordinated or controlled but should be considered and can be influenced over some longer time period.

What is inside the system boundary are the **system entities**. System entities include people, technology and procedures (International Civil Aviation Organization, 2018). A group of entities becomes a system when there are relationships, with the entities interacting to deliver the system functions. For purposeful systems, the entities cooperate to deliver the system purpose (Ackoff, 1971; International Civil Aviation Organization, 2018). For example, the purpose of air traffic control — the reason it exists — is to prevent collisions between aircraft. If the system entities act in their own self-interest and do not cooperate, the performance of the system degrades — in economics and game theory, this is called the **price of anarchy** (Papadimitriou, 2001).

The way we set the position of system boundaries defines what is inside and what is outside the boundaries and what the system will be. The boundaries are arbitrary and can be set depending on what we plan to study (Pruchnicki, 2019). When identifying the system boundaries, it helps to schematically represent them in a diagram. For example, in Figure 1 (p. 3) the red dotted line represents the system boundary for the system in question — in this case, a jet airplane. The entities inside the system that are considered important for the specific study are shown inside the system boundary, and those entities from the context that are relevant for the study are shown outside of the system boundary. The smaller box that is inside an entity box shows the individual function of the entity. For example, the entity "*Horizontal stabiliser*" provides the function "*Command pitch*" and the entity "*Engine*" provides the function "*Generate thrust*". For this specific example, the "*Flight crew*" entity that provides the function "*Manage flight*" is considered to be an entity in the system context.

For simplicity of representation, the entity interactions are not shown in the figure. In general, showing both structure and interaction makes the system diagram too busy. Alternatively, the interactions can be illustrated in function interaction diagrams, or influence diagram maps, or be described in a table format.

One system can be a part of another, larger system. This is the "system of systems" idea (Ackoff, 1971). As described by the International Civil Aviation Organization (2018): "*A total system safety approach considers the entire aviation industry as a system. All service providers, and their systems for the management of safety, are considered as sub-systems*." The systems can also form layered

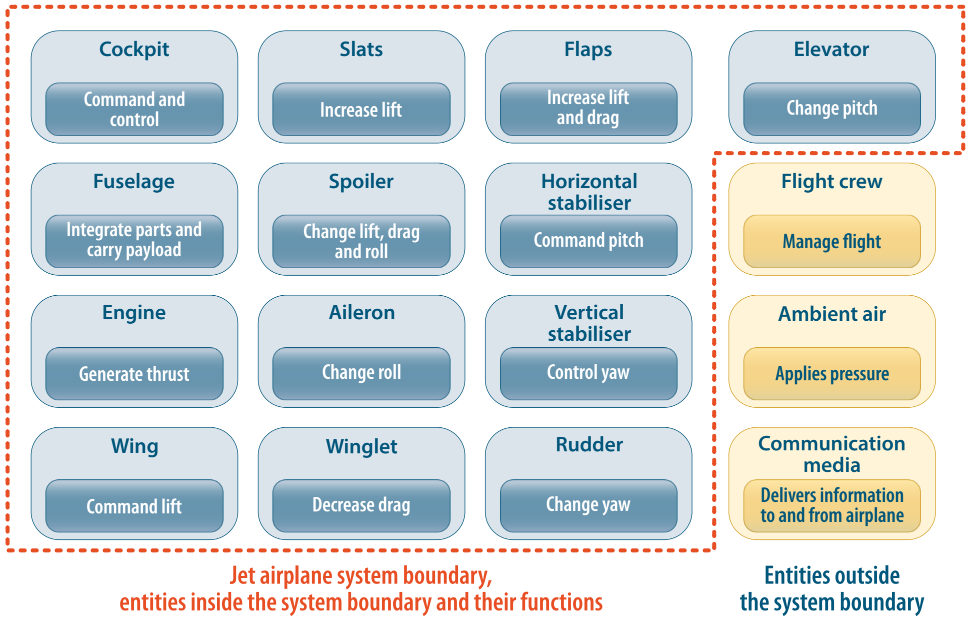

Figure 1: Jet airplane system

adaptive networks. For example, airports, air traffic control, flight dispatch, maintenance and air traffic flow control can interact as an adaptive network of systems.

A large part of understanding a system comes from understanding the network of interactions and interdependencies within the system and in the network of systems. As described by ICAO (2018), "*Often, a "system" is a collection of systems, which may also be viewed as a system with subsystems. These systems and their interactions with one another make up the sources of hazards and contribute to the control of safety risks*".

As described above, the way boundaries are set to define what is inside and what is outside the system is dependent on the question of interest. For example, we may wish to study flight crew interactions in the cockpit and with the aircraft. In this example, the system includes a flight crew and an aircraft, the boundary is the aircraft, and everything outside the aircraft is part of the environment of the system (Figure 2). In this example the system "*Jet airplane*" from Figure 1 is part of another, larger system — "*Flight*" which also includes the entity "*Flight crew*".

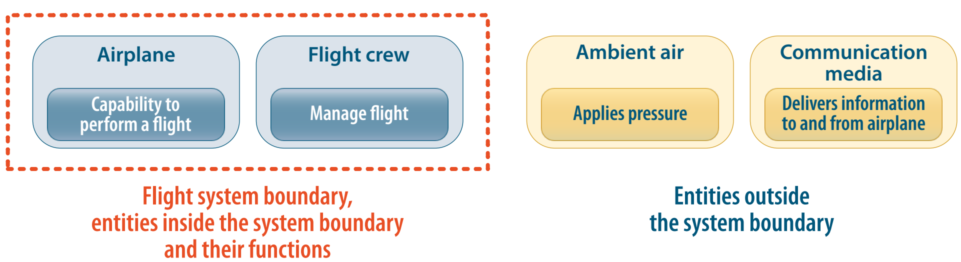

Figure 2: Flight as a system

But if we would like to study the function controller-pilot data link communication (CPDLC), then the system boundary will change and expand to include "*Flight crew*", "*Airborne CPDLC infrastructure*", the "*Ground CPDLC infrastructure*" and the "*Air traffic controller*" as the system in question (Figure 3, p.4).

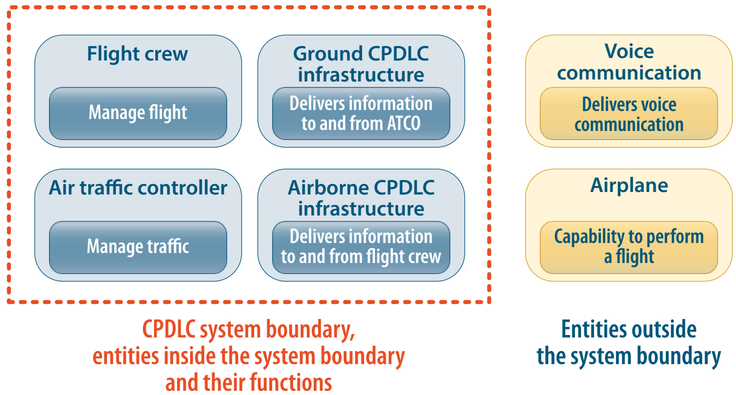

Figure 3: Controller-Pilot Data Link Communication (CPDLC) system

The presence of a human in a system presents unique opportunities and challenges (Sterman, 2002), including an intrinsic capability to learn and adapt, as well as sensitivity to a wide array of pressures and trade-offs of performance over different time horizons. This results in system behaviour that is less predictable.

Another effect of having a human in the systems is that the characteristics of system success and for system undesired behaviour can be quite different. That is, some studies (Herzberg, 1959; Buckingham, 1999) point out that factors that de-motivate people are not always just the opposite of the factors that motivate them. For example, factors like job security, salary and vacations are poorly associated with job satisfaction and motivation, though job dissatisfaction results from their absence.

1.3 System sharp end and system blunt end

Operations can be depicted as a system that has a **sharp end** and a **blunt end** (Reason, 1997). The sharp end includes parts of the system that are in immediate and direct interaction with flight operations. The sharp end includes pilots, air traffic controllers, operational processes and the technology used to perform the operational processes at a tactical level.

The blunt end of the system includes everything that is not on the sharp end. Depending on what the study objective is, the blunt end may not be restricted only to within an organisation. The blunt end may include corporate management, technology suppliers, regulators, policy-makers, government, international organisations and society.

Most of the demands, resources, incentives and constraints that the sharp end practitioners are confronted with are controlled and created at the blunt end of the system. In this way, the blunt end is either an enabler or an inhibitor for the resilient performance of the sharp end (Woods, 2010).

Safety and operational resilience are tactically created at the sharp end as practitioners interact with operations, using the available resources and responding to different pressures (Rasmussen, 1997; Woods, 2010). There are always pressures associated with operations (Rasmussen, 1997; Woods, 2015). In the vast majority of cases, the sharp end manages pressures and sustains system operations without any undesired outcome. The sharp end anticipates and responds to demands, accommodates variation and change, leverages opportunities and copes with unforeseen issues and surprises. This is sometimes done by closing the gap between plans, procedures and rules with the actual conditions encountered in real operations. **Learning From All Operations promotes understanding of and learning from sharp end adaptations regardless of their outcome.**

Operational adaptive processes happen at the sharp end but they are connected to and can be traced to processes at the blunt end. Often there is a significant time lag between the processes at the sharp end and the processes at the blunt end.

When a system is designed or analysed at the blunt end, the decision-making process is often performed with more time available and through top-down analysis of the environment, objectives, functions and system capacity. This approach is called **global rationality** (Simon, 1972). In contrast, decisions at the sharp end are made on a tactical level, often with limited time and information. In such situations, people do things that make sense to them given their goals, understanding of the situation and focus of attention at that time. This approach is called **local rationality** (Simon, 1972; Woods, 1999) and is performed by:

- Using local human-based heuristic strategies like approximate optimisation (reducing the complexity of the situation so that the decision-maker can handle it), satisficing (settling for a satisfactory, workable solution rather than an optimal solution) and framing (making a decision based on how the information is presented); or
- Using local technology-based strategies like gradient descent optimisation.

2. System dynamics

2.1 Emergence

The function of a purposeful system is not just a sum of the functions of the system entities (Kauffman, 1980). It is **emerging** as a result of the **interactions of the system entities** (Ackoff, 1971; Leveson, 2004; Hollnagel, 2006). In fact, this is why we bring the entities together — to interact and fulfil a purpose (Kauffman, 1980). But the benefits of these interactions can come at a price. The interactions of the system entities and system functions give rise to the emergence of other system phenomena — safety, reliability, performance and also undesired emergencies. The system can fail even when all the entities and interactions function well — for example, because of design omission or changes in the system context.

Even for a system with just few entities, the interaction of the system functions can become rather complex. Emergence occurs when the functions of entities interact through the functional relationships. For the example in Figure 3, the system function “CPDLC communication” emerges from the interaction of the system entity functions, and it is not depicted in this level of system representation. This “CPDLC communication” function cannot be attributed to just one of the entities or to be understood as a simple sum of the entities’ functions.

The interactions of the system entities are not always easy to understand as changes introduced at one entity of the system can propagate fast and far in the system and also spread in self-affecting loops. Basically, there are three ways to understand the emergence of system phenomena, and they involve Learning From All Operations:

- Learning from available information from the past — learning by precedent;
- Performing trials; and,
- Building and using system models — for example simulations.

If none of these three ways is feasible (for example, for unprecedented systems) then the only way to predict emergence is through involving people at the front end, like pilots and air traffic controllers, to reason about the system and its functioning. Involving front end professionals is, of course, also a necessary step in the other three ways to understand emergence.

Although many situations in aviation operations are predictable, some of the emergence will remain unpredictable and unknowable before the fact. Emergence may not be a result of a limited and understandable number of interactions but may result from myriad cumulative adjustments that reach a tipping point (Fiksel, 2015). Or, interactions can be triggered by an improbable or previously unknown event.

Purposeful systems "are more than the sum of the entities" — the ability of an aircraft to fly cannot be attributed to some sum of the entities' functions but also to their interaction. Looking at the system through the system entities' interactions is **holistic thinking**. This is different from "reductionist" thinking — separately studying the behaviour of each entity. Holistic thinking derives properties of parts from properties of the whole that contains them (Ackoff, 2004). Without considering the interactions, improvement in the performance of the system entities taken separately may not improve performance of the system as a whole.

2.2 System states

To understand the dynamics of system operations, it is useful to look at the states that the system can have along certain time periods. The state of a system at any moment is **the set of relevant properties** which the system has at that particular time (Ackoff, 1971). For example, the flight parameters, the distance between conflicting aircraft, the friction of tires on a runway surface, the remaining runway length, or the level of alertness of air traffic controllers.

As a system, aviation operations have an unlimited number of properties. But only some of these properties are relevant, considering the objectives of any specific study (Ackoff, 1971). Different Learning From All Operations studies will have different relevant properties, and the number of relevant properties may vary (Leveson, 2020).

In general, the operational system state can be defined in relation to a set of **multiple parameters in the system performance space** (Ackoff, 1971; Leveson, 2004; Hollnagel, 2006). The values of the relevant parameters will constitute the state of the system (Ackoff, 1971). During operations, the system dynamically transitions through the system states, which means that the values of the relevant parameters will change.

Depending on how exactly the system is defined, the system state can represent an entire flight as well as a certain aspect of an individual flight (e.g., loss of separation during this flight).

An example of the system states and their transitions is shown in Figure 4. Here the system that is studied is "Flight crew", and the selected relevant parameter is "One pilot level of alertness". As shown in the example, the alertness of the pilot transitions through several operating states. Initially, the level of alertness may increase to different states, depending on the factors that affect it, including the operational situation. It subsequently gradually decreases following the disappearance of the specific operational situation stimuli.

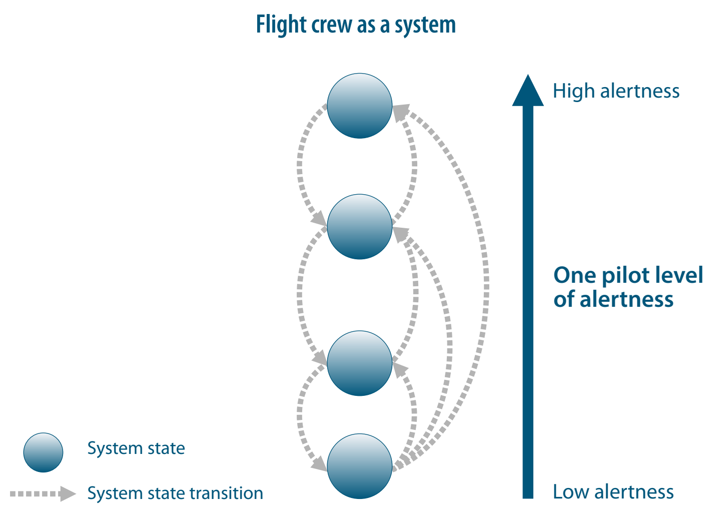

Figure 4: One pilot level of alertness example

System states may also represent some combination of more than one safety relevant parameter:

- Two parameters: flight envelope (a combination of speed and altitude); and,
- Multiple parameters: approach stabilisation criteria (SKYbrary, Stabilised Approach).

An example of system operating states represented by two relevant parameters is shown in Figure 5. In this example, the performance space is the airplane altitude envelope and the relevant parameters are the airplane speed and the altitude. The operating point of the aircraft transitions throughout certain states within the defined performance space from take-off and initial climb, through MACH climb, cruise, initial descent, approach and landing.

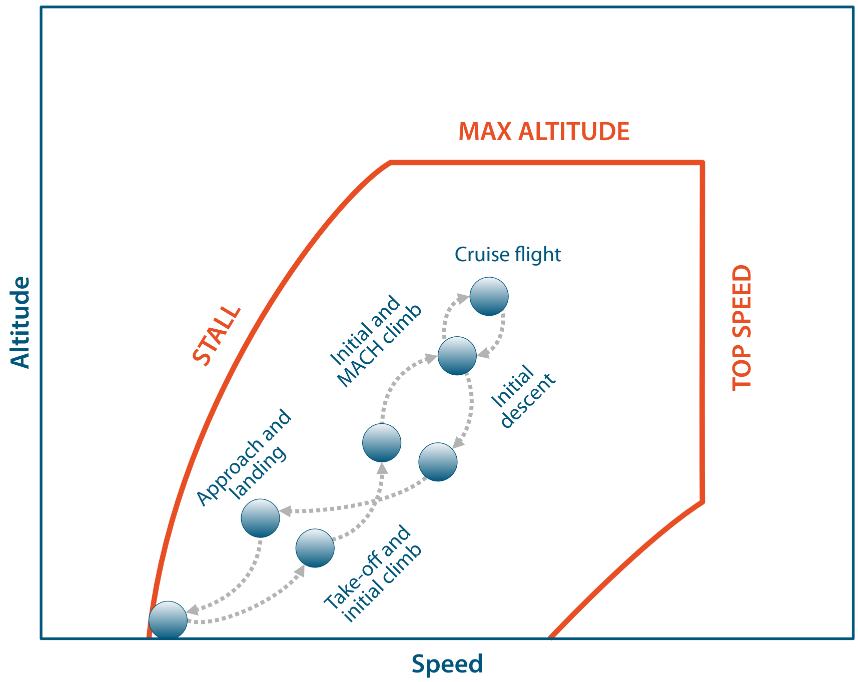

Figure 5: Flight envelope example

Depending on how exhaustive the study is, a system state can represent the operations as a whole, as well as certain aspects of this operations (e.g., the "risk of mid-air collision" for the whole operation).

Some of the system states will be **hazardous states** (Leveson, 2011). These are system states for which the level of control the system has in respect to safety becomes marginal. This is similar to the threat and error management (TEM) "undesired aircraft states" such as:

- Proceeding towards the wrong runway;
- Incorrect systems configuration; and,
- Unstable approach.

A hazardous aircraft state may arise because system adjustments are insufficient or inappropriate rather than because something fails (Hollnagel, 2006). Some research shows that, without continuous improvements, the systems will tend to migrate towards states with higher risk (Leveson, 2011). Some of this migration can be anticipated and addressed during system design. During system design and development, hazard analysis is used to identify hazardous states and to identify how the system can transition into the hazardous states (Leveson, 2020). Design strategies involve:

- Eliminating the possibility of a hazardous state;

- Preventing the system from transitioning to hazardous states;
- Reducing the occurrence of hazardous states;
- Providing system capabilities to recover from the hazardous states; and,
- Ensuring mitigations in terms of accident prevention or loss reduction once the system transitions to a hazardous state.

However, as **operations are only partially designed**, some of the hazardous states and the ways the system can get into those states will not be identified during system design and development. Additionally, complex systems may have so many potential states that exhaustively analysing all of them before system use may not be feasible (Leveson, 2011). Learning From All Operations helps to address the hazardous states and transitions that were not identified during design by learning and analysing the potential to adapt to what is encountered, even if it is unanticipated, unexpected or unpredicted.

3. Acknowledgements

This work was funded under grant and cooperative agreement 80NSSC21M0187 from the National Aeronautics and Space Administration's System-Wide Safety Project, part of the Aeronautics Research Mission Directorate's Aviation Operations and Safety Program.

This note was drafted by Tzvetomir Blajev from Flight Safety Foundation and by Dr. Jon Holbrook from NASA. Thank you to the members of the Flight Safety Foundation's Learning From All Operations Working Group, who contributed to the ideas and clarity of this report: Valerie Stait, Cathay Pacific Airways; Captain Tom Becker, TUI Fly; Captain Nick Peterson, American Airlines; Milena Studic, Skeyes; Captain Brian Teske, Delta Air Lines; George Hodgson, Southwest Airlines; Dr. Ricardo Patriarca, Sapienza University; and Captain Bertrand de Courville.

Suggested citation: Flight Safety Foundation. (2022). Learning From All Operations Concept Note 2: Systems Approach.

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