Trade-Offs as Symptoms of Mismatches Between Sociotechnical Systems: A Case Study involving Commercial Aviation and Air Traffic Control

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Abstract. Trade-offs occur frequently within sociotechnical systems and allow the system to maintain its output in the face of the variable performance of its constituent components. Trade-offs also occur between systems that must interact with each other. Some of these intersystemic tradeoffs may threaten the integrity of one or both systems particularly if the allowable magnitude of the trade-off is not clearly defined. Such unbounded trade-offs are symptomatic of fundamental mismatches between the goals of these interacting systems and represent a risk. These trade-offs can be eliminated by aligning the goals of the systems. In this way the required trade-off is made at the design stage and eliminates the need for the operators to undertake potentially risky trade-offs in dynamic, time-limited conditions.

1 INTRODUCTION

Much of the research undertaken in the field of complex sociotechnical systems explores the dynamics that occur within such systems (*intra*systemic). Far less work has been carried out to look at the interactions *between* such systems (*inter*systemic). The aim of the research on which this paper is based was to look at a safety significant event that occurs in commercial aviation known as the unstable approach.

Despite the high level of safety of commercial aviation relative to other forms of transport, approach and landing remain the phases of flight where accidents are most likely to occur (Civil Aviation Authority, 2008). During these phases of flight, pilot workload is high as it is necessary to change both the vertical and horizontal position of the aircraft whilst reducing its speed and altering its configuration by deploying landing gear and flaps in order to make landing possible (Lee & Liu, 2003).

The high proportion of accidents occurring during this phase of flight led to the Flight Safety Foundation implementing the Approach and Landing Accident Reduction (ALAR) Task Force. The ALAR Task Force found that unstabilised approaches were a causal factor in 66% of 76 approach and landing accidents and serious incidents between 1984 and 1997 (Flight Safety Foundation, 1999).

In order for an approach to be defined as stable, the aircraft must meet a certain set of criteria at a predefined height above the runway (usually 500ft or 1000ft depending on the meteorological conditions). Criteria include being on the correct flight path, speed within plus 20 knots and minus 0 knots of the calculated threshold speed for aircraft weight, landing gear down and flaps in landing position (Flight Safety Foundation, 2000). If an approach is unstable, the pilot must discontinue the approach and go-around (i.e. climb to a safe height and fly a predefined route with the option to return for a second approach). Whilst approaches that were too low or had insufficient speed tended to result in collision with the ground or with other terrain, approaches that were too high (based on distance from the runway) or too fast tended to result in runway overruns and excursions. The report also recognised that flight handling difficulties were often triggered by rushed approaches, adverse wind conditions and attempts to comply with inappropriate air traffic control (ATC) clearances.

The research carried out by the Flight Safety Foundation was undertaken in the 1990s, prior to the emergence of the field of resilience engineering. The research on which this paper is based was designed to take a 'systems perspective' on the phenomenon of unstable approaches in the hope of discovering system-based causes why this safety significant event continues to occur (Moriarty, 2011). The methodology included semi-structured interviews with pilots followed by analysis of the interview transcripts in order to identify how pilots decide when the speed and configuration (landing gear and flaps) of an aircraft should be changed in order to perform a safe approach and landing (i.e. what was the pilot's 'configuration plan'). Only findings relating to the interaction between pilots and air traffic controllers are given here.

2 TRADE-OFFS WITHIN AND BETWEEN SOCIOTECHNICAL SYSTEMS

2.1 General Systems Theory Applicable to Sociotechnical Systems

Von Bertalanffy first identified that mechanical, biological and social systems share some common characteristics that provide a common basis for talking about systems across several scientific fields (Von Bertalanffy, 1950). This position, known as general systems theory, gives rise to some recurring characteristics across systems (Kast & Rosenzweig, 1972) and some of those relevant to sociotechnical systems are given below:

1. Open systems – those which exchange information, energy or material with their surroundings;
2. System boundaries – separate the system from its surroundings. Less well-defined in open systems;
3. Multiple-goal seeking – different system subunits may have different goals;
4. Equifinality – biological and social systems operate differently to mechanical ones because system end-points can be achieved from a variety of different starting conditions using diverse inputs with varying internal activities.

Equifinality in a system suggests that there must be some variation in how components operate in order to achieve the same system output. This 'variability of normal performance' as a feature of system success (and system failure) is fundamental to the concept of safety in complex systems. Hollnagel first alluded to this variability in 2001 (Hollnagel & Amalberti, 2001) and later developed it into the principle of the Efficiency-Thoroughness Trade-Off (ETTO) (Hollnagel, 2002 & 2009). This paper focuses on trade-offs that occur between systems but it is worth briefly summarising why trade-offs occur within systems.

2.2 Intrasystemic Trade-Offs

Whilst variability of normal performance permits equifinality (and success) within a sociotechnical system, it also means that the system may function differently from one day to the next. Components within the system must adapt in order to accommodate variations in how other components are functioning, particularly in tightly coupled systems. In modelling sociotechnical systems, the Functional Resonance Analysis Method (Hollnagel, 2012) recognises that each function/activity has both an input and output as well as a possible time trigger/constraint. If the output of one activity is delayed and this output forms the input to another activity that is time-limited, the operator may have to perform an ETTO in order to preserve overall system function.

Another type of trade-off may occur as a response to an inefficiency in the design of the system. The interaction between two or more functions in the system may be inherently inefficient and so the operators come up with a 'work-around' that becomes a feature of the system, albeit an unofficial one.

2.3 Intersystemic Trade-Offs

Sociotechnical systems rarely operate in complete isolation. At various points along their boundaries, they will have to interact with other systems. Perrow (1984) gives an account of the interaction between two complex systems in his summary of the Lake Peigneur disaster of 1980. The unanticipated interaction between two systems with different goals (a company drilling for oil in Lake Peigneur and a mining company digging for salt beneath it) led to the loss of an oil rig and 3.5 billion gallons of water through a hole drilled into a mineshaft. This case study looked at the unfortunate outcome of an *unanticipated* interaction between two systems. What is of greater interest are the dynamics of *anticipated* system interactions.

3 INTERACTION BETWEEN COMMERCIAL AVIATION AND ATC

3.1 Commercial Aviation and ATC Interactions During the Approach Phase of Flight

When taking a systems perspective on the phenomenon of unstable approaches, one area of interest was the interaction between pilots and ATC. Commercial air transport is a system designed for the safe and efficient carriage of people and cargo by air. ATC is also a complex sociotechnical system, one designed to orchestrate the safe and timely flow of aircraft in and out of a particular volume of airspace. In the majority of cases, the goals of both systems are complimentary. There are cases, however, when the goals of one system may have a negative impact on the goals of the other. In the case of the crash of Southwest Airlines Flight 1455 in Burbank, California, ATC imposed altitude and speed restrictions on the pilots that limited their ability to achieve their goal; a stable approach (National Transportation Safety Board, 2002). In this case, two normally complimentary systems had two different goals that resulted in an accident after the aircraft landed at too high a speed, too far down the runway.

When pilots in the study were asked what lead them to have to change their preferred configuration plan, the most common reason cited was the need to comply with ATC instructions, such as ‘maintain 180 knots until 4 miles (from the runway)’. Although it was shown that pilots employed a wide range of tactics in dealing with ATC instructions that were unexpected or unusual, the regulations regarding compliance are quite clear and demonstrate the mismatch between the systems of air transport and ATC.

Regulatory authorities make it the responsibility of the pilot to comply with ATC instructions unless safety is an immediate priority. For example, section 91.123 of the Federal Aviation Regulations (Federal Aviation Administration, 1989) regarding compliance with ATC clearances and instructions states:

“When an ATC clearance has been obtained, no pilot in command may deviate from that clearance unless an amended clearance is obtained, an emergency exists, or the deviation is in response to a traffic alert and collision avoidance system resolution

advisory".

However, the Federal Aviation Authority, Order JO 7110.65T (Federal Aviation Administration, 2009), characterises the role of air traffic control services as follows:

"The primary purpose of the ATC system is to prevent a collision between aircraft operating in the system and to organize and expedite the flow of traffic".

These regulations mean that a pilot must comply with ATC instructions that may not be given for the purposes of separation but may instead be given for the purposes of expediency. The regulations do not recognise any requirement for facilitating a stable approach. Although pilots reported that their configuration plan was partly designed to permit an efficient approach, by far the most important influence on their configuration plan was the desire to guarantee a stable approach. The Flight Operations/ATC Operations Working Group of the Global Aviation Information Network undertook a survey of pilots and air traffic controllers regarding what they would like the other group to know about their respective jobs. Pilots responded that they would like controllers to be more aware of the criteria and importance of a stable approach (Global Aviation Information Network Working Group E, 2004).

From a systems perspective, during the approach phase of flight, there are two systems (the air transport system and the ATC system) using the same material (aircraft) in the same physical environment (the approach zone) at the same time to achieve two potentially different outcomes; stability for the pilots and separation/expediency for the air traffic controllers.

Based on interview responses, it is usually the pilot who has to make a trade-off in order to reconcile the mismatch between system goals, normally by modifying his or her normal configuration plan in order to comply with an instruction from ATC. For example, a pilot may normally reduce speed from 180 knots to 160 knots at 6 nautical miles from landing but may be put under pressure to delay this speed reduction until 4 nautical miles from landing at the request of ATC. Pilots also reported that requests from ATC usually came without warning and also came during the high workload phase of the approach. Pilots then have to quickly re-plan how they were going to configure the aircraft without having a clear idea whether these changes would threaten the stability of the approach.

The maximum extent of the trade-off (for example, the latest point at which a pilot could initiate a speed reduction) that would still guarantee stability would not be known to the pilot at the time. It is a function of, amongst other things, aircraft weight, wind conditions, approach angle and technical status of the aircraft. The multitude of variables means that the pilot cannot know for sure what size of trade-off will lead to instability and, in lacking this information, the trade-off they make is unbounded.

3.2 Unbounded Trade-Offs

For the purposes of this paper, an unbounded trade-off can be defined as one where the maximum safe extent of the trade-off is unclear to the operator at the time. If it becomes necessary to make such a trade-off, it may potentially threaten system success if it is too great. Unbounded trade-offs may occur intrasystemically in response to the varying performance of its components and may threaten system output if they are excessive. However, unbounded trade-offs that occur intersystemically may be seen as symptomatic of an inherent problem in how these systems interact rather than being a natural response to varying component performance.

Whilst we might expect there to be some variability in how systems interact with each other from day-to-day (as system outputs may vary slightly), when one system has to adjust its output substantially to satisfy the goals of the other without knowing in advance how much adjustment is safe, there is a risk of system failure. In the case of the interaction between air transport and ATC, there have been multiple occasions where ATC have issued clearances that have lead to pilots changing their approach configuration plan to such an extent that the approach has become unstable and, in some cases, the unstable approach has continued to a landing followed by the aircraft running off the end of the runway.

4 ALIGNING SYSTEM GOALS TO ELIMINATE UNBOUNDED TRADE-OFFS

If unbounded trade-offs are symptomatic of mismatches between the goals of two sociotechnical systems, once they are identified, steps should be taken to eliminate the need for them as they pose a risk to the functioning of one or both systems. When legislation was being drafted to regulate the air transport and ATC systems, it would have been clear to someone with knowledge of both systems that there was a potential mismatch in their goals. Unfortunately, systems tend to be designed by people with an in-depth knowledge of that particular system without full reference to the other systems that it will be interacting with.

One potential way of eliminating the need for an operator to make an unbounded trade-off in dynamic conditions is to make the trade-off *in advance*, at the design stage. If the goals of both systems are aligned so that rather than one system attempting to achieve separation/efficiency and the other trying to achieve stability, both systems aim for a more concrete goal such as getting the aircraft to fixed points along the approach path at predetermined speeds. These points along the approach are designed to guarantee stability and separation whilst still maintaining efficiency.

In this particular case, one concern might be that in changing the goals of the system, ATC might be prevented from maximising runway usage as controllers are adept at orchestrating an efficient flow of traffic to and from and airport. With many airports operating at their top capacity, any measures that would potentially decrease efficiency would need to be carefully weighed against reducing the risk of unstable approaches and the type of accident that results from them. It is worth reiterating that when an aircraft is not stable by a predefined height above the runway it must discontinue the approach and go-around. When we consider the issue of airport efficiency, the data available yields an interesting fact about the current perceived efficiency of the system. Data derived from the KLM fleet suggests the go-around rate is 15 per 1000 approaches and that the rate of go-arounds caused by unstable approaches is 3 per 1000 approaches (Speijker et al., 2000). The DGAC states that the rate of unstable approaches is 30 per 1000 approaches (Direction Générale de l'Aviation Civile, 2006). If pilots did as they were encouraged to and flew a go-around from every unstable approach, the go-around rate would almost triple to 42 per 1000 approaches. This would have a significant impact on ATC as nearly 1 in 20 approaches would result in a go-around. When viewed from this perspective it becomes clear that the current perceived efficiency of the system is predicated on pilots continuing unstable approaches to a landing.

5 CONCLUSIONS

Sociotechnical systems maintain system output (equifinality) partly because of trade-offs that occur between components. In a similar manner to trade-offs between components, trade-offs occur between systems that interact with each other because the system outputs are not always exactly the same. In some cases, trade-offs are made without knowing how large the trade-off can be before it threatens one or both of the systems. These unbounded trade-offs are symptomatic of fundamental mismatches in the goals of both systems and represent a risk.

One explanation for why these trade-offs occur is that each system tends to be designed by people with experience of that type of operation. Designers may be able to identify problem areas within their own system but it is unclear who has the responsibility for identifying problems that may occur *between* systems. Aligning the goals of potentially conflicting systems would eliminate the need for unbounded trade-offs. In essence, the designers of both systems agree the trade-off prior to the systems becoming active and it is then up to the operators to ensure that they commit to the aligned goals in the knowledge that it will deliver both the efficiency and the thoroughness desired by both systems.

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