Analysis of the human role in the resilience of air traffic management

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Abstract. The objective of this study is to identify and analyse strategies that are applied by pilots and air traffic controllers in dealing with a wide set of disturbances that may affect current air traffic operations. An extensive set of 459 disturbances is identified, which are clustered at three abstraction levels and characterised with respect to frequency of occurrence. Strategies of pilots and controllers for dealing with these disturbances are identified, and these strategies are also clustered at three hierarchical levels. The strategies are analysed with respect to key characteristics, such as detection and interpretation of the disturbances, coordination about the strategy, level of human flexibility, and strategy acquirement. The effects of the strategies on the key performance areas (KPAs) safety, capacity, environment and cost-efficiency are characterised and ranked. The results show that the strategies have positive safety implications for the majority of disturbances and negligible safety effects for the remaining cases. The effects on the other KPAs are negligible in the majority of cases, but they are negative for a variety of disturbances.

1 INTRODUCTION

Air Traffic Management (ATM) is a complex sociotechnical system involving large numbers of interacting human operators and technical systems, which function in different organisations at a variety of locations, and do their job in the context of uncertainty and disturbances (e.g., delays, weather, system malfunctioning, airspace closure). The ability of the ATM system to sustain operations by adjusting its functioning in the face of a wide range of disturbances is recognized as an important asset. The introduction of this resilience perspective in ATM has been supported considerably by the Resilience Engineering research field (Eurocontrol, 2009; Hollnagel et al., 2006; Woltjer, 2009).

Although procedures and regulations tend to specify working processes in ATM to a considerable extent, the flexibility and system oversight of pilots and air traffic controllers are essential for efficient and safe operations in normal and uncommon conditions (Eurocontrol / FAA AP15 Safety, 2010). In choosing suitable strategies for dealing with disturbances, the human operators have to balance the interacting and potentially counteracting effects on ATM key performance areas (KPAs), prominently including safety, capacity, and cost-efficiency. Some types of disturbances can be handled well at an early stage environment by human operators, other types of disturbances are more difficult to handle efficiently, and the strategy may come at the cost of particular KPAs.

The objective of this study is to obtain an overview of strategies that are applied by pilots and air traffic controllers in dealing with a wide set of disturbances that may affect current ATM operations, and to characterise the effectiveness of these strategies for attenuating the effects of disturbances with regard to KPAs in ATM.

This paper is structured as follows. Section 2 presents the identification of disturbances in ATM, clustering of these disturbances and an assessment of their frequency. Section 3 presents the identification, clustering and characterization of strategies for dealing with the disturbances. Section 4 presents an assessment of the effects of the strategies on KPAs in ATM. Section 5 presents a discussion of this research.

2 DISTURBANCES IN ATM OPERATIONS

2.1 Identification of disturbances

Resilience is the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions (Eurocontrol, 2009). As a basis for the analysis of the human role for resilience in ATM, there is a need for a wide list of disturbances that may perturb its operations and thereby require actions from human operators.

For the analysis in this study we adopt a wide list of events, conditions and circumstances that may occur in current and future ATM operations (Stroeve et al., 2011). These events, conditions and circumstances have been identified during brainstorm sessions with pilots, controllers and other experts, as part of a large number of ATM safety assessment studies. These sessions used 'pure brainstorming' guidelines (De Jong, 2004), wherein the participants were asked to identify as many as possible events, conditions and circumstances that may perturb ATM operations, and to refrain from criticism and/or analysis of their potential effects. They have resulted in a wide variety of disturbances, which may influence ATM KPAs, including safety, capacity, environment and cost-efficiency.

The list of disturbances of (Stroeve et al., 2011) contains 525 items, which cover a wide range of subjects including technical systems in aircraft and in the ATC system, performance of pilots and controllers, communication and coordination in ATM operations, weather, traffic relations, etc. Examples of disturbances related to technical systems are ‘Degradation of the brake system of an aircraft’, ‘Trajectory disappears from FMS’, ‘Radar is not working’, and ‘Flight plans of ATC system and FMS differ’. Examples of disturbances related to human operators are ‘Pilots report wrong position’, ‘Pilot mixes up different types of ATC clearances’, ‘Controller corrects wrong aircraft’, ‘Controller switches wrong stopbar off’, and ‘Pilot is fatigued’. Examples of disturbances related to traffic relations are ‘Speed differences between aircraft in a sequence’, ‘Emergency flight’, and ‘Unknown flying objects, e.g. weather balloons, leisure balloons, paragliders’. Examples of disturbances related to weather are ‘Reduced visibility’, ‘Runway is more slippery due to rain, snow, icing’, and ‘Wind influences expected time of arrival’.

2.2 Clustering of disturbances

The collection of disturbances describes a wide variety of events and conditions that may occur in air transport operations. As a starting point for the analysis of the human role to resilience in ATM, these disturbances are clustered. In this way the set of disturbances is structured and the number of types of disturbances that needs to be evaluated is reduced.

The clustering process describes the disturbances at three hierarchical levels of abstraction and forms subsets of disturbances on these hierarchical levels:

- Low-level: detailed description of a disturbance;
- Mid-level: an aggregation of a number of related low-level disturbances;
- High-level: a generic principle of a group of mid-level types of disturbances.

Disturbances are clustered with regard to similarity of the source of the disturbance, such as disturbances due to particular technical systems, disturbances resulting from particular human operators, or disturbances arising in particular processes. For example, high-level disturbance clusters include ‘Aircraft/navigation technical systems’, ‘Controller pilot communication’, ‘Controller working context’, ‘Pilot performance’, and ‘Weather’. The high-level cluster ‘Aircraft/navigation technical systems’ contains mid-level disturbance clusters such as ‘Accuracy of FMS routing’ and ‘Instrument landing system’, and the latter cluster includes specific low-level disturbances, such as ‘Wrong localizer frequency of the instrument landing system’, ‘Technical ILS failure’ and ‘Failure to capture or track the precision approach lateral or vertical guidance’. The details of the three-level clustering of disturbances are reported in (Stroeve et al., 2013).

The total set of disturbances contains 525 items. A number of 66 disturbances are out of the scope of this study, since they refer to future operations or to security issues. The remaining 459 disturbances have been clustered in 18 high-level disturbance categories and 149 mid-level disturbance categories. The mid-level disturbance categories contain in the range of 1 to 16 low-level disturbances. In half of the disturbances (229 out of 459), pilots or air traffic controllers may contribute to the existence of the disturbance, e.g. misconceptions of human operators, or errors in task performance. The other half of the disturbances are not somehow the resultant of the performance of pilots and controllers.

2.3 Frequencies of disturbances

The frequency of the occurrence of the mid-level disturbances has been assessed using four flight-based frequency categories, ranging from more than once every 100 flights to less than once every million flights. This frequency assessment is based upon expert opinions expressed during a dedicated workshop with pilots and air traffic controllers, results in the literature, and judgements by NLR safety experts. The frequency assessment is quite rough, since specific contextual factors, which may have a considerable influence on the frequency of the disturbance, have not been taken into account in this assessment.

The results show that the whole pallet of frequency categories is applied to characterise the disturbances, ranging from very rare disturbances, such as general system outages or evacuation of ATC centres, to regular disturbances, such as workload problems, aircraft speed differences and poor weather conditions (Stroeve et al., 2013). The majority of the identified mid-level disturbances occur more often than once every 10,000 flights. Thus the set includes many disturbances that are quite common, as well as a range of rarer disturbances.

3 STRATEGIES FOR DEALING WITH DISTURBANCES

3.1 Identification of strategies

Identification of strategies for dealing with the disturbances has been achieved by a dedicated workshop with pilots and controllers, by results in the literature, and by judgements of NLR experts. For each of the 149 mid-level disturbances, the strategies of pilots and controllers for dealing with them are described in detail in (Stroeve et al., 2013). In addition to these detailed strategy descriptions, for each mid-level disturbance one or a few key strategy elements have been identified, which summarize the main aspects of the strategies applied by pilots and controllers.

3.2 Clustering of strategies

As a basis for structured analysis of the strategies, a clustering of the strategies has been done, both for the strategies of controllers and pilots. Similar to the clustering of disturbances in Section 2.2 and similar to the resilience markers framework of (Furniss et al., 2011), the clustering uses three hierarchical levels of abstraction:

- Low-level: detailed description of a strategy, which is an identified key strategy element;
- Mid-level: an aggregation of a number of related low-level strategies;
- High-level: a generic principle of a group of mid-level strategies.

The strategies of controllers are clustered at 7 high-level strategies, 27 mid-level strategies and 98 low-level strategies (Stroeve et al., 2013). The high-level strategy clusters of air traffic controllers are:

- Adapt to context – describing strategies to deal with differences between airlines, large workload, and situations lacking procedures;
- ANSP organisational task – describing tasks within the ANPS organisation such as reporting of problems, safety management and training;
- ATC-pilot interaction – describing all kinds of communication actions between controllers and pilots, such as providing instructions and information, or requesting information;
- Configuration management – describing management of airspace or airport configurations, for instance in reaction to weather conditions;
- Coordination & information provision – describing coordination actions between controllers as well as with other entities (e.g., airline, vehicle driver);
- React to non-nominal situations – describing the application of contingency and emergency procedures; and
- Tactical control cycle – describing planning, monitoring, and interventions during tactical control as strategies to deal with disturbances.

The strategies of airline pilots are clustered at 7 high-level strategies, 25 mid-level strategies, and 71 low-level strategies. The high-level strategy clusters of pilots are:

- Adapt to context – describing strategies to deal with large workload, and situations lacking procedures;
- Airline organisational task – describing tasks within the airline organisation such as reporting of problems, safety management and training;
- ATC-pilot interaction – describing all kinds of communication actions between controllers and pilots, such as providing instructions and information, or requesting information;
- Coordination & information provision – describing coordination and information provision actions within the crew as well as with some other entities (e.g., other aircraft, passengers);
- Flight control – describing flight planning, monitoring and control by the pilots;
- React to environment – describing strategies to deal with weather conditions; and
- React to non-nominal situations – describing the application of contingency and emergency procedures.

3.3 Characteristics of strategies

Each strategy for dealing with a mid-level disturbance is characterized with respect to:

- First detection of disturbance - Which human operator or which technical system may detect the disturbance first?
- Establish common ground – Which kinds of communication/coordination actions are done to achieve a common understanding of the disturbance and of its effect on the operation?

- Strategy coordination – What kinds of communication/coordination actions are done in the strategy to deal with the disturbance?
- Level of human flexibility in strategy – What is the level of human flexibility in the strategy?
- Strategy acquirement – In what way has the strategy been acquired?

The results show that most mid-level disturbances can be detected at first instance by pilots (71%) and/or controllers (82%), but that only a minority of the disturbances can be detected via a notification or alert of a technical system (19%) (Stroeve et al., 2013). The analysis also shows that there are always some kinds of interactions between human operators to interpret the disturbance and to achieve a strategy, where most coordination is at the level of the controllers at local facilities, cockpit crew and air-ground interaction. For the majority of strategies medium to high levels of human flexibility are required, and these are mainly based upon a combination of training and experience. It appears that the precise application of the strategy mostly depends on the specific circumstances and cannot be based on standardized actions only.

4 EFFECTS OF STRATEGIES ON KEY PERFORMANCE AREAS

A qualitative assessment has been made of the effects of the strategy for dealing with disturbances on the main ATM key performance areas, regarding safety, capacity, environment and cost-efficiency. For each mid-level disturbance an assessment of the effect of the strategy on each KPA has been made on a 5-class scale (large negative, small negative, negligible, small positive, large positive). Next, by combining the frequency of the disturbance and the effect of the strategy on the KPA, a ranking for each KPA has been determined, where the strategies with the largest effects that deal with the most frequent disturbances rank highest (Stroeve et al., 2013).

Table 1. Effects of strategies for dealing with disturbances on ATM key performance areas. The percentages relate to the number of associated mid-level disturbances.

Effect	Safety	Capacity	Environment	Costs
Large negative	0.0%	9.4%	6.7%	8.1%
Small negative	0.0%	17.4%	20.8%	22.1%
Negligible	20.8%	65.1%	68.5%	64.4%
Small positive	49.7%	8.1%	4.0%	5.4%
Large positive	29.5%	0.0%	0.0%	0.0%

Table 1 shows a summary of the effects of the strategies by pilots and controllers on the ATM key performance areas. The results show that the strategies have positive safety implications in about 79% of the mid-level disturbances and negligible effects on safety for the remainder of the disturbances. This result indicates the safety priority of these operators working at the sharp end in ATM, when dealing with disturbances. Rankings of the effect of mid-level strategies on the KPAs are listed in (Stroeve et al., 2013). Examples of strategies with considerable positive safety implications include communication and coordination actions for explanation, verification and correction, monitoring and intervention actions in the tactical control cycle, and using different traffic configurations depending on weather conditions. These strategies can all be recognized as being very normal in ATM and such normal actions are important for maintaining safety in day-to-day operations.

For the other key performance areas (capacity, environment and cost-efficiency) the effects of the strategies are negligible in the majority (64% - 69%) of the disturbances, but the strategies also have negative implications in a considerable number of cases (27% - 30%). Prominent negative implications arise from weather-related disturbances (e.g., low visibility, strong winds, winter conditions, thunder storms) and from disturbances related to the ANSP organisation and workforce (e.g. strikes, controller shortage). The strategies to deal with such disturbances are aimed at maintaining safety and typically lead to considerable reductions in capacity, increase in delays, additional miles flown per flight, and decrease in cost-efficiency.

5 DISCUSSION

As a way to understand the human role in the resilience of ATM, we performed a qualitative analysis of the strategies of pilots and air traffic controllers in dealing with a large set of 459 disturbances that may occur during current air traffic operations. These disturbances stem from a considerable number of 'pure brainstorming' sessions for the assessment of the safety of air traffic operations. Since the 'pure brainstorming' guidelines prohibit analysis during the sessions, a wide diversity of disturbances has been identified, which may have effect on various KPAs. Notwithstanding the size and variety of the set of identified disturbances, it is recognized that the disturbances are mostly focused on the air traffic operations themselves, i.e. they are mostly disturbances on the sharp end in the ATM organisation. For processes, humans and technical systems that reside more towards the blunt end of the ATM organisation, other disturbances may also be relevant for the resilience of the overall ATM system.

Given the broad scale of the study, the large number of mid-level disturbances and the generality of the assessment, the assessment results provide a rather rough overview of the implications of the strategies on the various KPAs. A more precise characterisation of the effects can be achieved in more detailed assessments that take into account the specific context of the disturbance occurrences, and the potential interactions between a variety of disturbances.

The results show that pilots and controllers have a safety priority when being faced with disturbances. In the majority of disturbances, their performance is focused on improving the level of safety given the disturbance occurred, and in the remaining cases the effect on safety is negligible rather than negative. In contrast, negative implications of the strategies exist in a considerable number of cases (27%-30%) for the KPAs capacity, environment and cost-efficiency. The observed safety priority in the strategies does not mean that the performance of pilots and controllers cannot have negative safety effects. In half of the disturbances, pilots or air traffic controllers may contribute to the existence of the disturbance (e.g. misconceptions, errors) and the net effect of human-induced disturbances and the mitigating strategies may still be negative for safety. To well assess the overall effect on safety, more detailed studies, which take into account the context of a specific operation, are needed.

In conclusion, we identified, hierarchically clustered and characterized a large set of disturbances that may occur in ATM operations. The majority of these disturbances are quite common. We identified, hierarchically clustered, and characterized strategies of pilots and controllers for dealing with these disturbances. Interactions between human operators and medium to high levels of human flexibility are typical ingredients of these strategies. We assessed the implications of the strategies on ATM KPAs. Most strategies have positive safety effects, which come at the expense of negative effects on other KPAs in a considerable number of disturbances.

ACKNOWLEDGEMENTS

The research presented in this paper is done as part of the Resilience2050.eu project and is funded by the Seventh Framework Programme of the European Commission. We thank all participants of the Resilience2050 Task 1.2 workshop for their contributions, and we are grateful to the Turkish ANSP DHMI and the Technical University of Istanbul ITU for their support in its organisation.

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