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NLR-TP-2015-204

# Analysis of the roles of pilots and controllers in the resilience of air traffic management

S.H. Stroeve
B.A. van Doorn
M.H.C. Everdij

Anthony Fokkerweg 2, 1059 CM  Amsterdam, P.O. Box 90502,1006 BM Amsterdam, The Netherlands
T: +31 88 511 35 00, F: +31 88 511 32 10, E: info@nlr-atsi.nl, I: www.nlr-atsi.nl

## Executive summary

# Analysis of the roles of pilots and controllers in the resilience of air traffic management

**Problem area**
Resilience in air traffic management (ATM) means the intrinsic ability of the ATM 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. It is well realized that human operators have key contributions to resilience of operations. There are various resilience analysis approaches that describe the work-as-done of human operators along various viewpoints, typically by textual descriptions. The objective of this paper is to present an effective and structured qualitative approach for the resilience analysis of large sets of disturbances and strategies for work-as-done at the sharp end of a complex sociotechnical system. This is pursued by studying the roles of air traffic controllers and airline pilots in achieving resilience in current-day air traffic operations. Air traffic controllers and airline pilots are key operators working at the sharp end of air traffic operations. In their work they have to deal with a large variety of potential disturbances and in their strategies they need to balance the effects on a range of key performance areas (KPAs), e.g. safety, capacity, environment and costs. We consider quite generically that a disturbance in ATM somehow perturbs air traffic operations and thereby may affect the performance in one or several of its KPAs.

**Description of work**
The starting point of the study was a list of disturbances that were identified during hazard brainstorm sessions. We used interview sessions and a workshop with pilots and controllers to gather data about strategies for dealing with disturbances. A set of 459 disturbances were clustered at three abstraction levels and characterised with respect to frequency of occurrence. Strategies of pilots and controllers for dealing with these disturbances were identified, and these strategies were clustered at three hierarchical levels. The strategies were analysed with

**Report no.**
NLR-TP-2015-204

**Author(s)**
S.H. Stroeve
B.A. van Doorn
M.H.C. Everdij

**Report classification**
UNCLASSIFIED

**Date**
May 2015

**Knowledge area(s)**
Vliegveiligheid

**Descriptor(s)**
resilience
air traffic management

This report is based on an paper published in Safety Science, Volume 76, pages 215-227, 2015

respect to key characteristics, such as detection and interpretation of the disturbances, coordination about the strategy, and strategy acquirement. The effects of the strategies on the KPAs safety, capacity, environment and cost-efficiency were characterised and ranked.

**Results and conclusions**
This paper developed approaches for systematic structuring of large sets of disturbances and strategies for analysis of resilience of a complex sociotechnical system. This structuring was achieved by hierarchical clustering of disturbances and strategies in ATM, by systematic characterization of key aspects of the strategies, by classification of effects on KPAs, and by combining these effects and disturbances frequency classes. We found that the majority of the disturbances in ATM are quite common and that the human roles in detection and interpretation of the disturbances, as well as in coordination to achieve a suitable strategy are important. Assessment of the implications of the strategies on ATM KPAs showed that most strategies have positive safety effects, which may come at the expense of negative effects on other KPAs for a variety of disturbances. These results emphasize the important roles of pilots and controllers for dealing resiliently with disturbances in ATM and balancing the implications on the operational performance of their actions. Design principles for future more automatized ATM should take well into account these important human roles.

**Applicability**
The approach used in this paper can be applied to systematic structuring of large sets of disturbances and strategies for analysis of resilience in complex sociotechnical systems, such as ATM.



NLR Air Transport Safety Institute

Anthony Fokkerweg 2, 1059 CM Amsterdam,
P.O. Box 90502, 1006 BM Amsterdam, The Netherlands
Telephone +31 88 511 35 00, Fax +31 88 511 32 10, Web site: http://www.nlr-atsi.nl

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# ANALYSIS OF THE ROLES OF PILOTS AND CONTROLLERS IN THE RESILIENCE OF AIR TRAFFIC MANAGEMENT

S.H. Stroeve
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*This report is based on a paper published in Safety Science, Volume 76, pages 215-227, 2015.*



| | |
|---|---|
| **Customer** | National Aerospace Laboratory NLR |
| **Owner** | National Aerospace Laboratory NLR |
| **Division** | Air Transport |
| **Distribution** | Unlimited |
| **Classification of title** | Unclassified |
| | May 2015 |

Approved by:

| Author<br>S.H. Stroeve | Reviewer<br>Anonymous external reviewers via Safety Science | Managing department<br>A.D.J. Rutten |
|---|---|---|
| Date: 28-5-2015 | Date: 28-5-2015 | Date: 28-5-2015 |

# Summary

The objective of this paper is to show how qualitative resilience analysis approaches can be effectively structured for large sets of disturbances and strategies for work-as-done at the sharp end of a complex sociotechnical system. This is pursued by studying the roles of air traffic controllers and airline pilots in dealing with a wide set of disturbances in current air traffic operations. Disturbances are events or conditions that may affect one or more components or processes of the ATM system and thereby perturb air traffic operations. A set of 459 disturbances 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, 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 for dealing with disturbances 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. The results emphasize the important roles of pilots and controllers for dealing resiliently with disturbances in ATM.

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# Contents

# 1 Introduction

The concept of resilience has gained considerable interest for the design and analysis of sociotechnical systems. As outlined in reviews of (Folke, 2006; Francis, 2013), the origins of the resilience perspective stem from ecological studies on the dynamics and interactions of prey and predator populations, including a core paper of Holling (Holling, 1973). In the early 1990s the resilience perspective for the analysis of ecosystems revived and was also extended to socio-ecological systems. In (Folke, 2006; Walker et al., 2004), resilience is defined as the capacity of a system to absorb disturbance and to re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedback. In general, a disturbance is an event that is (potentially) detrimental to one or more components or processes within a system (Francis, 2013). What constitutes a disturbance depends on the system context, e.g. in ecological systems a disturbance typically refers to something that leads to loss of biomass, such as a forest fire, hurricane, or a new predator. The analysis of resilience of sociotechnical systems has been stimulated considerably by safety-related research of Hollnagel and co-workers and their introduction of the resilience engineering research field (Hollnagel et al., 2006; Nemeth et al., 2009). This has led to the identification of Safety-II, i.e. a way of understanding safety beyond the traditional way (Safety-I). Hollnagel et al. (2013) make clear that the focus of Safety-II is on everyday actions and outcomes, rather than the restricted view on (rare) accidents and incidents in Safety-I. As such, Safety-II can be understood as studying safety via a work-as-done viewpoint in resilience engineering.

Various views exist on key aspects of resilient systems and ways to assess resilience. According to Hollnagel (2009) the four essential cornerstones for a resilient system are the abilities to respond to the actual, to monitor the critical, to anticipate the potential, and to learn from the factual. Following an extensive review of resilience in a variety of fields, Francis and Bekera (2014) conclude that absorptive, adaptive and restorative capacities are at the core of a resilient system, indicating capacities to absorb system perturbations, to adjust to undesirable situations by undergoing change, and to return to an acceptable level of operations, respectively. For the assessment of resilience in air traffic management (ATM), Woltjer et al. (2013) use the following principles: work-as-done (understanding the way work is done, including operator performance variability, rather than the work-as-imagined); varying conditions (considering expected and unexpected conditions that may be encountered); signals and cues (considering the information for anticipation, monitoring, and response by operators to varying conditions); goals trade-offs (understanding the trade-off operators make between various goals); adaptive capacity (considering the capacity to adjust to foreseen and unforeseen varying conditions); coupling and interactions (considering the complexity and distributed nature of the ATM sociotechnical system); timing, pacing, and synchronization (understanding the dynamics of the ATM sociotechnical system); under-specification and approximate adjustments (considering the incompleteness of procedures and the adjustments operators have to make in their work-as-done). These principles were applied in a workshop format for analysis of resilience of a future ATM operation. Furniss et al. (2011) developed a resilience markers framework for reasoning about resilience in small teams, which studies behaviour in a hierarchy of three levels of abstraction (from high to low): a markers level describing the high-level principle, a strategy level expanding on details of the marker level, and an observation level describing the detailed work-as-done in a particular context. The strategy level is structured by four elements: a resilient repertoire, encompassing the skills and competencies to respond to threats and vulnerabilities outside the design-base; a mode of operation, describing the style, structure or organisational mode in an operational context; resources and enabling conditions, describing the hard and soft constraints that influence whether a strategy can be enacted; and vulnerabilities and opportunities, describing events and conditions that, respectively, may reduce or improve system performance. The resilience markers framework was applied in a case study for analysis of control room crews of a nuclear power plant using a re-analysis of previously recorded simulator experiments. Rankin et al. (2014) developed a strategy framework for analysis of resilience in everyday operations. It uses the following categories for structuring work situations: strategies, describing mechanisms used to cope with variations; objectives of strategies; forces and situational conditions, describing the context in which strategies are carried out; resources and enabling conditions, describing necessary conditions for successful strategies; resilience abilities, referring to the four cornerstones of (Hollnagel, 2009); sharp-end and blunt-end interactions, describing how a strategy has impact on different parts of a distributed system. In addition to these strategy categories, Rankin et al. (2014) developed a variety space diagram, which relates the frequency of a disturbance, the availability of responses to cope with a disturbance, and the level of sharp- and blunt-end interactions in a strategy. The approach has been applied using results of group discussions between safety practitioners on safety-critical situations in various domains (e.g. health care, nuclear power, air traffic control). In summary, these resilience analysis approaches all describe work-as-done using various viewpoints along strategy categories and principles. The results are mostly textual descriptions of work-as-done along these viewpoints. In the applications such results were derived for selected operations by workshops or analysis of simulator experiments.

The objective of this paper is to present an effective and structured qualitative approach for the resilience analysis of large sets of disturbances and strategies for work-as-done at the sharp end of a complex sociotechnical system. This will be pursued by studying the roles of air traffic controllers and airline pilots in achieving resilience in current-day air traffic operations. Air traffic controllers and airline pilots are key operators working at the sharp end of air traffic operations. In their work they have to deal with a large variety of potential disturbances and in their strategies they need to balance the effects on a range of key performance areas (KPAs), e.g. safety, capacity, environment and costs. We consider quite generically that a disturbance in ATM somehow perturbs air traffic operations and thereby may affect the performance in one or several of its KPAs. Examples of disturbances in ATM are bad weather, system malfunctioning, airspace closure, and misunderstandings. In the context of ATM, resilience has been defined similarly to (Folke, 2006; Walker et al., 2004) as 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). The resilience engineering perspective stresses the flexibility and system oversight of pilots and air traffic controllers as being essential for efficient and safe operations in normal and uncommon conditions (Eurocontrol, 2009; Eurocontrol / FAA AP15 Safety, 2010). As a way towards the main objective, we have the following sub-objectives:

- To identify and hierarchically structure disturbances in air traffic operations and assess their frequency of occurrence;
- To identify strategies (work-as-done) by pilots and controllers for dealing with disturbances;
- To hierarchically structure strategies of pilots and controllers;
- To analyse the strategies w.r.t. detection, coordination and strategy acquirement in the organisation;
- To evaluate the effects of disturbances on the ATM KPAs safety, capacity, environment, and cost-efficiency;
- To derive statistics for the analysis results;
- It is expected that the approaches developed in this paper for ATM can also be used to study resilience in other complex sociotechnical systems with large numbers of potential disturbances.

This paper is structured as follows. Section 2 introduces the main sources used as input for the analysis. Section 3 presents the identification of disturbances in ATM, the clustering of these disturbances and an assessment of their frequency. Section 4 presents the identification, clustering and characterization of strategies for dealing with the disturbances. Section 5 presents an assessment of the effects of the strategies on KPAs in ATM. Section 6 presents a discussion of this research.

Parts of this research were presented in a conference paper (Stroeve et al., 2013a).

# 2 Main sources for the analysis

As input for the analysis we have used three main sources: a list of disturbances (Section 2.1), interviews with pilots and controllers (Section 2.2), and a workshop with pilots and controllers (Section 2.3).

## 2.1 List of disturbances

There exist a broad variety of events, conditions and circumstances that may disturb air traffic operations. As a starting point for the analysis in this paper we use a list of disturbances that was presented in (Stroeve et al., 2011). The basis for this list are disturbances that were identified during hazard brainstorm sessions with pilots, controllers and other experts, as part of a large number of ATM safety assessment studies. Key objectives of these brainstorm sessions were to identify as many as possible events, conditions and circumstances that may potentially have a negative effect on safety, and to refrain from any criticism and/or analysis during the brainstorm (De Jong, 2004). As result of these 'pure brainstorming' sessions, a wide variety of events, conditions and circumstances that may occur during ATM operations were identified, which were not analysed or restricted to situations that affect safety only. Therefore, such brainstorming sessions resulted in a wide variety of disturbances that may perturb ATM operations and thereby possibly influence various ATM key performance areas, including safety, capacity, environment and cost-efficiency. For example, an identified disturbance is 'group of passengers arriving late at the gate', and the resulting delay may lead to more stress on the pilots from a safety perspective, and to an increase in costs due to accumulated delays from a cost perspective. In an earlier study (Stroeve et al., 2011), a database of more than 4,000 disturbances identified in the hazard brainstorm sessions was processed in order to remove similar disturbances and to de-identify them for specific air traffic operation contexts. This led to a set of 525 disturbances, which is input for the current study.

## 2.2 Interviews with pilots and controllers

Interviews were conducted with air traffic controllers and airline pilots in order to find out how these operators detect and deal with disturbances that may occur in current air traffic operations. The purpose of the interviews was to obtain feedback about the way that the disturbances may be coped with in the operators' normal work, building on their operational knowledge and experience. In preparation of the interviews, a selection of 98 disturbances was made, and for each of these disturbances questions were formulated with respect to ways that operators may detect and deal with the disturbances.

Interviews were conducted with five air traffic controllers (all active) and two pilots (one active and one recently retired). The expertise of the controllers includes positions at area, approach and tower control; both pilots were airline pilots. One of the controllers was also a supervisor, another had experience as an aircraft technician, and a third controller had experience as a general aviation pilot. The interviewees originated from four different European countries. In preparation of the interviews, the interviewees were sent the questionnaire forms, such that they could get an initial overview of the issues that would be addressed. They were not asked to complete the questionnaires in advance of the interviews. The interviews were conducted either face-to-face (3 interviews) or by telephone (4 interviews), and each lasted about three hours. The interviews were structured according to the questionnaire forms. In the interviews the pilots and controllers were asked to consider the way that the disturbances may be coped with in their normal work, building on their operational knowledge and experience. Some of the disturbances and the related questions were skipped during the interviews, because they were not considered relevant given the interviewee background, because the issue raised had already been discussed previously, or because of time restrictions. After each interview, minutes were provided and were sent to the interviewee for verification. The results of the interviews are reported in (Stroeve et al., 2011).

## 2.3 Workshop with pilots and controllers

A two-day workshop was organized, involving eight air traffic controllers, two airline pilots, and one avionics technician. One of the controllers was also a supervisor. These controllers and pilots were different from the pilots and controllers that contributed to the interview sessions explained in Section 2.2. During the workshop 58 clusters of disturbances, including a total of 225 disturbances, were presented by a moderator and projected on a screen for everybody to see. The participants were asked for their opinion about the frequency of occurrence of the disturbance, to explain how they would detect the occurrence of the disturbance, and to explain their strategy to deal with the disturbance. The responses were typed on screen for all to follow. After the workshop, minutes of the meeting, describing all answers, were distributed and verified by the participants.

# 3 Disturbances in ATM operations

Section 3.1 presents the selection of disturbances used in this study, Section 3.2 presents the clustering of disturbances, and Section 3.3 describes frequencies of these disturbances in air traffic operations.

## 3.1 Set of disturbances

The disturbances used in this study are a part of the list of 525 disturbances introduced in Section 2.1. In particular, a number of 66 disturbances are out of the scope of the current study, since they refer to future operations and/or future technical systems, or to security issues. As such, 459 disturbances remain as basis for this study. To clarify the broadness of the set of disturbances, some examples are presented next.

Examples of disturbances related to technical systems are (1) Degradation of the brake system of an aircraft; (2) Trajectory disappears from flight management system (FMS); (3) Radar is not working; (4) Flight plans of air traffic control (ATC) system and FMS differ; (5) Different coding of curves by different suppliers of flight management systems; (6) Blind spots in radar coverage. It can be recognized that these examples reflect different types of technical system disturbances. The first three are temporary and typically sudden failure conditions. The fourth example is an inconsistency between air and ground systems, which is typically temporary for (part of) a flight. The last two examples reflect disturbances that are typically enduring and which may be considered as part of normal operations.

Examples of disturbances related to human operators are (1) Pilots report wrong position; (2) Pilot mixes up different types of ATC clearances; (3) Controller corrects wrong aircraft; (4) Controller switches wrong stopbar off; (5) Pilot is fatigued; (6) Complacency of a controller. The first four disturbances may be considered as erroneous events. Fatigue and complacency in the last two examples are conditions that may be enduring for longer times.

Examples of disturbances related to communication and coordination are (1) Failure in frequency changes between subsequent air traffic controllers; (2) Pilot reads back erroneously; (3) Controller and pilot communicate in a foreign language rather than English; (4) Lack of suitable radio telephony (R/T) phraseology. The first two disturbances may be considered as erroneous events.

The third disturbance may be considered as temporary event, but also as a part of a cultural attitude. The fourth disturbance is an enduring condition, which may become manifest in particular situations.

Examples of disturbances related to traffic relations are (1) Speed differences between aircraft in a sequence; (2) Emergency flight; (3) Unidentified flying objects, e.g. weather balloons, leisure balloons, paragliders. The first disturbance is a typically occurring situation, which may be considered as normal variation in traffic streams. The latter two disturbances are sudden events.

Examples of disturbances related to weather are (1) Reduced visibility; (2) Runway is slippery due to rain, snow, icing; (3) Wind influences expected time of arrival. These disturbances typically are temporarily occurring conditions.

The above examples indicate that a wide variety of disturbances has been identified. The disturbances may be related to various components in the ATM socio-technical system (human operators, technical systems, procedures) and to interactions between the components. The disturbances include ATM external influences, such as weather and other flying objects. The disturbances may be sudden and temporary events, or they may reflect enduring normal variations in the operations.

## 3.2 Clustering of disturbances

As a starting point for the analysis of the human role to resilience in ATM, the disturbances were clustered. In this way the set of disturbances was structured and the number of individual disturbances that needs to be evaluated was reduced. The clustering process describes the disturbances at three hierarchical levels of abstraction and it forms subsets of disturbances on these levels:

- Low-level: detailed description of a disturbance, being the description in the set of disturbances;
- 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 were 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'.

A summary of the results of the clustering is provided in Table 1; details of the three-level clustering of disturbances are reported in (Stroeve et al., 2013b). The 459 disturbances have been clustered into 18 high-level disturbance categories and in 149 mid-level disturbance categories. The mid-level disturbance categories contain 1 to 16 low-level disturbances. In about half of the disturbances (229 out of 459), pilots or air traffic controllers somehow may contribute to the existence of the disturbance, e.g. misconceptions of human operators, or errors in task performance.

*Table 1. Clustering of disturbances at three hierarchical levels. The grey boxes contain the high-level disturbance clusters, the left column presents all mid-level disturbance clusters, the right column present examples of the low-level disturbances and it provides the total number of low-level disturbances in a high-level cluster*

| Mid-level disturbance clusters | Low-level disturbances | |
|---|---|---|
| | **Size** | **Examples** |
| Aircraft/navigation technical systems | | |
| Accuracy of FMS routing ; Aircraft equipment level ; Cockpit display ; Conflict resolution advisory system ; Error in FMS routing ; False/nuisance alert ; Fuselage ; Generic airborne system ; Instrument landing system ; Landing system ; Positioning system ; Powerplant | 36 | • False alert of an airborne system<br>• Trajectory disappears from FMS<br>• Degradation of landing gear<br>• GPS signal is disturbed at low altitudes<br>• Degradation of engines |
| Airport infrastructure & operations | | |
| Aircraft ground movement ; Airport configuration ; Airport design ; Approach / runway lights ; Approach and landing ; Bird strike ; Fire brigade ; Maintenance work / obstacle ; No ATC ; Runway blocked or contaminated ; Vehicle movement | 30 | • Runway closed<br>• Small aircraft parking places<br>• Animals on the runway<br>• High object close to runway (building, crane) |
| Airspace | | |
| Airspace availability ; Airspace design ; Change in airspace availability | 6 | • Restricted airspace<br>• Closure of airspace (e.g. due to emergency, volcanic eruption) |
| ATC coordination | | |
| Conflict / emergency ; Coordination military operations ; Coordination overload ; Different procedures / algorithms at ATC centres ; Error / delay ; Language & cultural differences at ATC centres ; Planning & tactical ; Shift change ; Traffic handover ; Traffic level | 28 | • Military aircraft not VHF equipped<br>• Miscommunication between controllers<br>• Different cultures at coordinating ATC centres<br>• Confusion about who has control<br>• Traffic overload at sector boundary |
| ATC System | | |
| Aircraft identification ; Alert not properly provided ; ATIS ; False/nuisance alert ; Flight | 57 | • Mislabelled identity<br>• Display does not show alert |

| Mid-level disturbance clusters | Low-level disturbances | |
|---|---|---|
| | Size | Examples |
| plan ; General system outage ; Human machine interface ; Non-adaptable system mode ; Radar ; Strips ; Surveillance data distortion & delays ; System controller interaction ; Track problem ; Transponder problem | | • Controller display is cluttered<br>• Blind spots in radar coverage<br>• Track swap |
| Controller performance | | |
| Allowance to deviate from normal procedure ; Erroneous data entry ; Improper system use ; Mode selection ; Monitoring ; No checking ; Professional attitude ; System not effectively used ; Wrong / late decision ; Wrong or missing message | 23 | • Controller switches wrong stopbar off<br>• Controller does not use alert system<br>• Controller makes error in typing a message<br>• Controller misuses equipment |
| Controller pilot communication | | |
| Aircraft identity ; Communication system ; No suitable phraseology ; Non-standard / poor R/T ; R/T misunderstanding ; R/T overload ; VHF frequency selection | 35 | • Controller mixes up company names<br>• Lack of suitable R/T phraseology<br>• VHF R/T frequency is blocked |
| Controller situation awareness | | |
| Aircraft capability ; Aircraft identity ; Aircraft intent ; Aircraft mode ; Aircraft state ; Airspace separation mode ; Alert interpretation ; Contradictory information ; Detection & interpretation of traffic situation ; Infrastructure & system functionality ; Reading error ; System trust | 40 | • Controller misidentifies an aircraft<br>• Controller does not know airspace configuration<br>• Controller ignores an alert (no evaluation)<br>• A controller not aware of work in progress |
| Controller working context | | |
| Aircraft identity ; Automation ; Controller incapacitation ; Distraction ; Evacuation ; False failure report ; Organisation & workforce ; Training & experience ; Workload | 27 | • Controller is fatigued and sleepy<br>• Evacuation of ATC centre (e.g. fire alarm)<br>• Strikes |
| Delay | | |
| Delay | 3 | • Missing passenger, aircraft has to wait or return to the gate |
| Flight performance | | |
| Aircraft performance limitation ; Extreme movements ; Fuel shortage ; Uncommanded movements ; Wrong direction | 8 | • Aircraft flies near its envelope extremes<br>• Fuel shortage |
| Maintenance | | |
| No proper repair ; No regular check | 5 | • Technicians cannot fix a failure quickly |
| Pilot performance | | |
| ATC instruction/clearance ; Cockpit crew coordination ; Data entry ; Deviation from normal procedures ; Late reaction ; Monitoring ; Position & intent reporting ; Wake vortex reaction ; Wrong / uncertain decision | 43 | • Pilots do not follow controller instruction<br>• Checklist procedures not yet finished<br>• Pilots report wrong position<br>• Pilot validates without actually checking |
| Pilot situation awareness | | |
| Alert interpretation ; Controller situation ; Crew difference ; Detection & interpretation of traffic situation ; Event detection ; Routing ; Rules and procedures ; Runway choice ; System degradation ; System mode ; System | 32 | • Alert causes attention tunnelling<br>• Pilot confuses radar heading with a flight level<br>• Aircrew unaware of loss of voice communication |

| Mid-level disturbance clusters | Low-level disturbances | |
|---|---|---|
| | Size | Examples |
| trust | | |
| Pilot working context | | |
| Cultural differences ; Distraction ; Interaction with technical system ; Pilot incapacitation ; Safety culture ; Training ; Workload / information load | 18 | • Pilot performance is affected due to alcohol, drugs or medication<br>• Pilot insufficiently trained for new concept |
| Rules and procedures | | |
| Changes in procedures ; Differences between procedures ; No suitable procedure available ; Procedure not tested ; Procedure restricts operational flexibility ; Unclear / difficult procedures ; Wrong procedure design | 19 | • Change in ATC procedures leads to confusion by pilots<br>• Contingency procedures have not been tested<br>• Wrong design of procedure |
| Traffic relations | | |
| Aircraft speed differences ; Complex operations ; Conflict propagation ; Emergencies ; Other flying objects ; Traffic density ; Traffic mix ; Wake vortex separation | 24 | • Speed differences between aircraft in a sequence<br>• Resolution of conflict leads to other conflict(s) |
| Weather | | |
| Darkness ; Icing of wings ; Lightning ; Low visibility ; Pilot performance ; Technical systems ; Turbulence ; Weather info ; Wind ; Winter conditions at airport | 25 | • Sudden strong descent of cloud base<br>• Weather forecast wrong<br>• Strong variation in wind |
| **Total number of low-level disturbances** | **459** | |

## 3.3 Frequencies of disturbances

As a basis for the analysis of effects of disturbances in ATM, an assessment was done of the frequency of their occurrence. Table 2 shows the four frequency classes used in this assessment, which are based upon the probability of occurrence of a disturbance per flight for commercial fixed-wing aviation in Europe. For an airport with 300,000 flights per year, these probability levels roughly imply: Very Rare – Fewer than 3 times per 10 years; Rare – Between 3 times per 10 years and 30 times per year; Occasional – Between 30 times per year and 4 times per day; and Regular – More than 4 times per day. For prolonged disturbances the number of affected flights is leading. For instance, if there are snow conditions 10 days per year and these conditions have impact on 3% of the yearly flights, then this disturbance is considered to be Regular, since the probability per flight is more than 0.01.

*Table 2. Definition of frequency classes for probability of occurrence of disturbances per flight for commercial fixed-wing aviation in Europe*

| Frequency class | Probability per flight |
|---|---|
| Very rare | Less than $10^{-6}$ |
| Rare | Between $10^{-6}$ and $10^{-4}$ |
| Occasional | Between $10^{-4}$ and $10^{-2}$ |
| Regular | More than $10^{-2}$ |

Using these categories, we assessed frequencies of occurrence for each of the mid-level disturbances of Table 1. Sources used for this frequency assessment were expert opinions expressed during the workshop and interviews, and results in the literature. One or multiple frequency categories were selected for each mid-level disturbance. Multiple frequency categories were chosen for cases where the underlying low-level disturbances apply to different frequency categories. It is noted that 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.
An overview of the distributions of the frequency classes is shown in Figure 1. The results show that the whole pallet of frequency categories is applied to characterise the disturbances, ranging from very rare disturbances, e.g. general system outages or evacuation of ATC centres, rare disturbances, e.g. pilots using a wrong runway, occasional disturbances, e.g. changes in ATC procedures leading to confusion by pilots, and regular disturbances, e.g. workload problems, aircraft speed differences and poor weather conditions. A total of 109 mid-level disturbances have a single frequency category, whereas the remaining 40 mid-level disturbances have at least two frequency categories associated. 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.

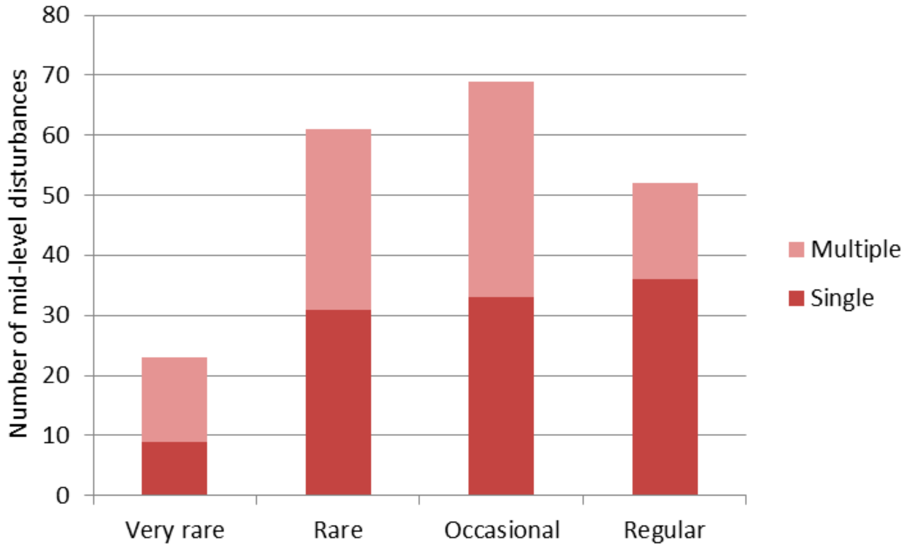


*Figure 1. Use of frequency categories for the mid-level disturbances. 'Single' denotes cases where the frequency category is applied uniquely. 'Multiple' denotes cases where the frequency category is part of a range*

# 4 STRATEGIES FOR DEALING WITH DISTURBANCES

Given a disturbance in an air traffic operation, pilots and controllers often have a choice of strategies that they can apply. Section 4.1 describes the identification of such strategies, Section 4.2 describes the clustering of these strategies, and Section 4.3 provides an overview of characteristics of the strategies.

## 4.1 IDENTIFICATION OF STRATEGIES

By using results of the workshop, the interviews, and the literature, we identified pilot and controller strategies for dealing with the disturbances. For each of the 149 mid-level disturbances, the pilot and controller strategies for dealing with them were detailed in (Stroeve et al., 2013b). Additionally, for each mid-level disturbance one or a few key strategy elements were identified, which summarize the main aspects of the strategies.

In this way, for air traffic controllers, a total of 97 key strategy elements were identified, e.g. 'Extra control of flights of particular airlines', 'Ask pilot to report condition', 'Close runway', and 'Update weather information'. For airline pilots, a total of 71 key strategy elements were identified, e.g. 'Report system failure', 'Inform ATC about inconsistency', 'De-icing of the wings', and 'Follow procedures for system failures'.

## 4.2 CLUSTERING OF STRATEGIES

To promote a structured analysis of the pilot and controller strategies, the strategies were first clustered. Similar to the clustering of disturbances in Section 3.2 and similar to the resilience markers framework for studying resilience of small teams by (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.

Table 3 shows an overview of the clustering of controller strategies, as well as the numbers of mid-level disturbances to which these strategies are applied. The controller strategies are clustered into 7 high-level strategies, 27 mid-level strategies, and 97 low-level strategies. As an example, the high-level strategy 'Adapt to context' includes three mid-level strategy clusters 'Adapt to differences between airlines', 'Improvisation', and 'Workload management', and the first mid-level strategy cluster includes the low-level strategies 'Adapt to cultural differences', 'Effectively deal with differences between airlines', 'Extra control of flights of particular airlines', and 'Speak slowly in R/T with particular airlines'. Table 3 shows that the high-level strategy clusters 'Tactical control cycle' and 'ATC-pilot interaction' have the highest numbers of low-level strategies. These clusters include many strategies that are at the core of the daily operations, such as instructing and informing pilots, and monitoring and planning traffic.

*Table 3. Strategies of air traffic controllers for dealing with disturbances. The grey boxes contain the high-level strategy clusters, the left column presents all mid-level strategy clusters, the right column presents examples of low-level strategies and it provides the total number of low-level strategies in each high-level cluster*

| **Mid-level strategy clusters** | **Low-level strategies** | |
|---|---|---|
| | **Size** | **Examples** |
| Adapt to context | | |
| Adapt to differences between airlines ; Improvisation ; Workload management | 10 | • Extra control of flights of particular airlines<br>• Use necessary R/T only |
| ANSP organisational task | | |
| Inform pilots ; Management ; Reporting problems to organisation ; Safety management ; Training and experience | 13 | • Report inappropriate procedure<br>• Inform technicians<br>• Additional training |
| ATC-pilot interaction | | |
| Coordinate with pilots ; Provide information to pilots ; Provide instructions to pilots ; Request information from pilots | 24 | • Explain traffic context<br>• Inform pilots on routes and procedures<br>• Adapt instruction following feedback from pilots<br>• Split up clearance<br>• Ask pilot to report condition |
| Configuration management | | |
| Manage airport configuration ; Manage airspace configuration ; React to environmental condition | 11 | • Close runway<br>• Split sectors<br>• Use low visibility procedures |
| Coordination & information provision | | |
| Coordination with controller ; Coordination with others ; Provide information | 12 | • Coordinate with other controllers<br>• Coordinate with airline<br>• Update weather information |
| React to non-nominal situations | | |
| Apply contingency procedures ; Follow emergency procedures | 8 | • Apply contingency procedures<br>• Use alternative system<br>• Inform fire brigade |
| Tactical control cycle | | |
| Apply separation criteria ; Error correction ; Evaluation of information ; Monitoring of traffic ; Planning of traffic ; Pro-active control ; Tactical solution | 19 | • Correct mistake<br>• Continuous evaluation of information from various sources<br>• Extra monitoring of aircraft |

| **Mid-level strategy clusters** | **Low-level strategies** | |
|---|---|---|
| | **Size** | **Examples** |
| | | • Give priority to flight<br>• Use margins for variance in performance between aircraft |
| **Total number of low-level strategies** | **97** | |

Table 4 provides an overview of the strategies used by airline pilots. These are clustered into 7 high-level strategies, 25 mid-level strategies, and 71 low-level strategies. The high-level strategy clusters with most elements at the lowest level are 'React to non-nominal situation', 'ATC-pilot interaction', and 'Flight control'. These clusters include strategies for normal daily operations as well as strategies for rarer non-nominal situations.

*Table 4. Strategies of airline pilots for dealing with disturbances. The grey boxes contain the high-level strategy clusters, the left column presents all mid-level strategy clusters, the right column presents examples of the low-level strategies and it provides the total number of low-level strategies in each high-level cluster*

| **Mid-level strategy clusters** | **Low-level strategies** | |
|---|---|---|
| | **Size** | **Examples** |
| Adapt to context | | |
| Improvisation ; Workload management | 4 | • Deal in a flexible and professional way with the situation lacking proper procedures |
| Airline organisational task | | |
| Management ; Reporting problems to organisation ; Safety management ; Training and experience | 12 | • Schedule effectively coordinating crews<br>• Report system failure<br>• Fatigue risk management programme |
| ATC-pilot interaction | | |
| Coordination with ATC ; Follow ATC instructions ; Provide instructions to ATC ; Request information from ATC | 16 | • Ask for priority<br>• Inform ATC about inconsistency<br>• Ask controller for clarification on procedures |
| Coordination & information provision | | |
| Crew resource management ; Provide information to others ; Request information from others | 3 | • Inform passengers about extreme movements<br>• Ask other aircraft for the correct frequency |
| Flight control | | |
| Deal with (potential) conflicts ; Evaluation of information ; Flight planning ; Follow operating procedures ; Make corrections ; Pro-active control | 14 | • See and avoid<br>• Avoid extreme movements<br>• Check fuel |
| React to environment | | |
| Adapt operation ; Use applicable procedures | 6 | • Avoid cumulonimbus clouds<br>• De-icing of the wings |
| React to non-nominal situation | | |
| Adapt operation ; Follow (upset) recovery procedures ; Follow emergency procedures ; Use fall-back solution | 16 | • Reduce weight and return<br>• Follow procedures for system failures<br>• Use alternative system |
| **Total number of low-level strategies** | **71** | |

## 4.3 Characteristics of strategies

Key aspects of strategies for dealing with disturbances in operations include understanding who or what may detect the disturbance first; what kinds of interactions are used for achieving a common ground (Klein et al., 2005), i.e. a common understanding by the involved human operators about the disturbance and its potential effect on the operation; what kinds of interactions are used for coordinating about selection of the most appropriate strategy; and how has the strategy been acquired. We characterised the strategies for dealing with mid-level disturbances by classifying disturbance detection, establishing common ground, strategy coordination, and strategy acquirement by the following elements.

*First detection of disturbance* – Which human operator or which technical system may detect the disturbance first? One or several of the following may apply:

- *Controller* – A controller may detect the disturbance first.
- *Pilot* – A pilot may detect the disturbance first.
- *System notification/alert* – A system notification or alert may be the origin of the detection of the disturbance.
- *Other* – Another origin of the first detection, e.g. an airport operator, a cabin crew member, a meteorologist, etc.

*Establish common ground* – Which kinds of interactions are used to achieve a common understanding of the disturbance and its effect on the operation?
*Strategy coordination* – Which kinds of interactions are used in achieving a strategy to deal with the disturbance?
Both establishing common ground and strategy coordination are characterised by selecting one or several of the following interaction classes:

- *No* – No actions to achieve common ground / coordinate about a strategy.
- *Local-Ground* – Common ground / coordination between air traffic controllers (including executive and planning controllers, and supervisor) at a local control facility (tower, control room).
- *Global-Ground* – Common / coordination ground between air traffic controllers at different control facilities.
- *Local-Air* – Common ground / coordination of the cockpit crew (and possibly also the cabin crew).
- *Global-Air* – Common ground / coordination of the cockpit crew during flight with others in the airline organisation, e.g. Airline Operations Centre.
- *Ground-Air* – Common ground / coordination between air traffic controller and cockpit crew.

- *Org-Ground* – Common ground / coordination at the level of the ANSP organisation, e.g. Safety Manager, operational concept developers, technicians, …
- *Org-Air* – Common ground / coordination at the level of the Airline organisation, e.g. Safety Manager, Airline Operations Centre, …
- *Other* – Common ground / coordination with e.g. maintenance, meteo, airport personnel, fire brigade, …

*Strategy acquirement controller* – In what way has the strategy been acquired by a controller?
*Strategy acquirement pilot* – In what way has the strategy been acquired by a pilot?
One or several of the following classes may apply:

- *Training* – The strategy has been acquired via training (basic / recurrent / special).
- *Experience* – The strategy has been acquired via practical experience.
- *Creativity* – The strategy is based upon creativity.
- *n.a. (not applicable)* – Strategy acquirement is not applicable for controller or pilot.

Figure 2 shows an overview of the statistics for the assessed characteristics of the strategies for dealing with the disturbances. Detailed results are available in (Stroeve et al., 2013b).

It follows from Figure 2a that most often, controller and pilots can detect a disturbance first. To a considerably smaller extent, the disturbances can be detected first by a system, e.g. via an alert function, or by another means than controller/pilot/system. As follows from the sum largely exceeding 100%, there are many disturbances that can be detected first by multiple entities, depending on the specific circumstances.

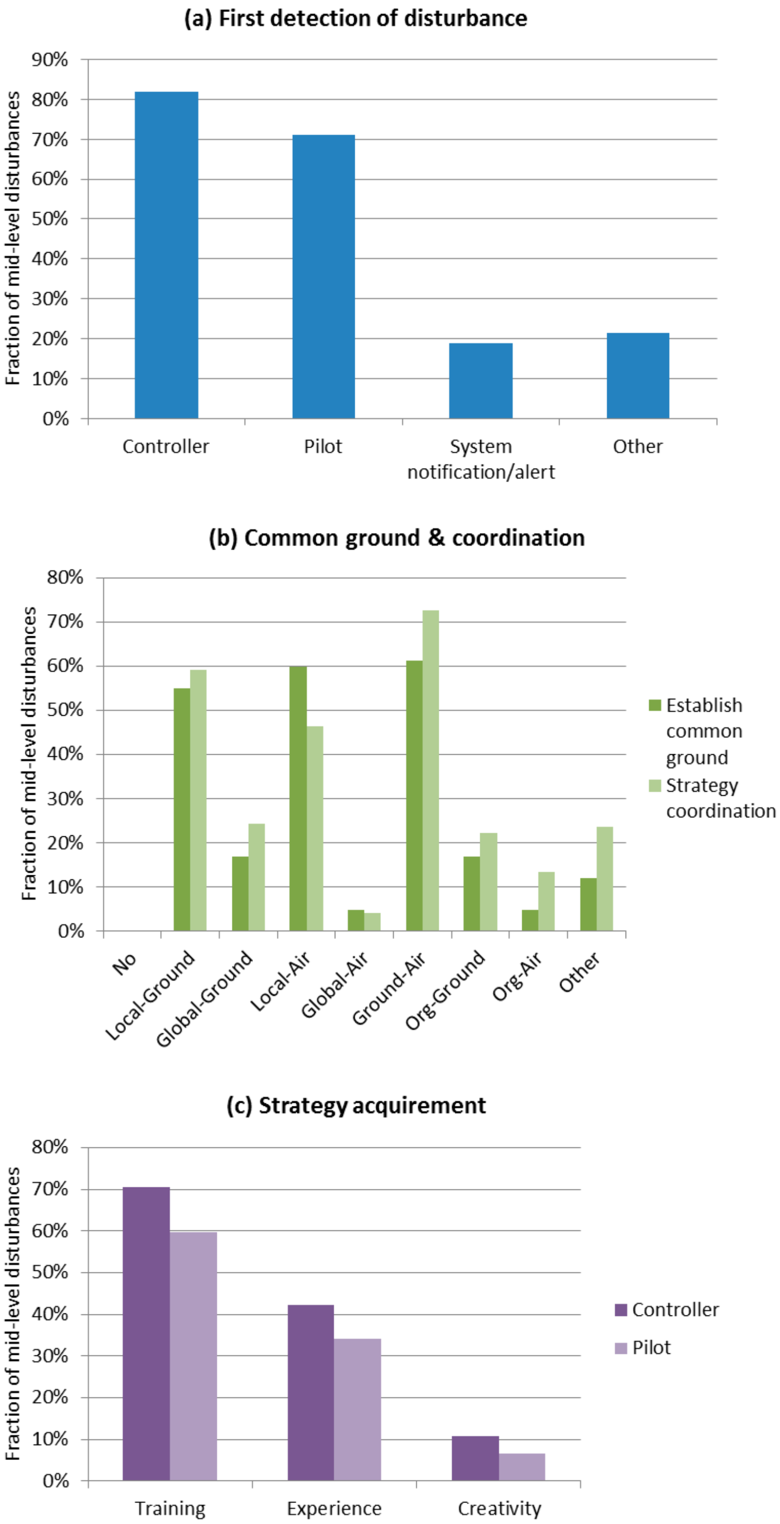


*Figure 2. Characteristics of strategies for dealing with disturbances in ATM*

Following the detection of a disturbance, there can always be some kind of communication or coordination between involved actors as a way to achieve a common understanding of the disturbance and its effect on the operation ('Establish common ground'). Figure 2b shows that such common ground is established to a large extent by interaction between pilot and controller, by interaction between controllers at a local facility, and by interaction of the aircraft crew. To a lesser extent a common ground is achieved by interaction between controllers at different control facilities, by interaction at the ANSP organisation, by interaction with others in the airline during flight, by interaction within the airline at an organisational level, or by other types of interactions.

In line with the results for establishing common ground about the disturbance, coordination about the strategy is achieved to a large extent by interaction between pilot and controller, by interaction between controllers at a local facility, and by interaction of the aircraft crew (see Figure 2b). To a lesser extent the strategy is coordinated by interaction between controllers at different control facilities, by interaction at the ANSP organisation, by interaction with others in the airline during flight, by interaction within the airline at an organisational level, or by other types of interactions.

Figure 2c indicates that to a considerable extent the acquirement of the strategies is based on training and experience for both controllers and pilots, and to a lesser extent it is based on creativity.

# 5 EFFECTS OF STRATEGIES ON KEY PERFORMANCE AREAS

A qualitative assessment was made of the effects of the strategies for dealing with disturbances on the main ATM key performance areas (KPAs), regarding safety, capacity, environment and cost-efficiency. Section 5.1 provides a high-level overview of the KPA effects. Section 5.2 provides results for the KPA effects of clusters of strategies employed by controllers and pilots. Section 5.3 provides results for the KPA effects of clusters of disturbances.

## 5.1 OVERVIEW OF KPA EFFECTS

For each of the 149 mid-level disturbances, we assessed the effect on each of the four KPAs of the pilot and controller strategies for dealing with the disturbance. This assessment was done qualitatively on a 5-class scale (Table 5) by judging each mid-level disturbance in isolation and by reasoning on the relative effect of the strategies on the KPAs.

*Table 5. Definition of quality indicators for ATM KPAs*

| | Safety | Capacity | Environment | Costs |
|---|---|---|---|---|
| **Large positive (LP)** | Large decrease in probability of incident/accident | Large or enduring increase in capacity | Less emissions or noise impact for many aircraft | Less costs for many aircraft |
| **Small positive (SP)** | Small decrease in probability of incident/accident | Small increase in capacity for a short time | Less emissions or noise impact for 1 or a few aircraft | Less costs for 1 or a few aircraft |
| **Negligible (Neg)** | Negligible change in probability of incident/accident | Negligible change in capacity | Negligible impact on emissions or noise | Negligible impact on costs |
| **Small negative (SN)** | Small increase in probability of incident/accident | Small decrease in capacity for a short time | More emissions or noise impact for 1 or a few aircraft | More costs for 1 or a few aircraft |
| **Large negative (LN)** | Large increase in probability of incident/accident | Large or enduring decrease in capacity | More emissions or noise impact for many aircraft | More costs for many aircraft |

Next we provide some examples of this qualitative assessment; the details of all assessments are available in (Stroeve et al., 2013b).

- The disturbance "Low visibility" is handled by using low visibility procedures by pilots and controllers, implying that pilots may need to taxi at lower speeds or use auto-landing systems, and controllers use larger separation distances and verify aircraft positions more intensively. Such strategies for low visibility conditions are assessed to have a large positive effect on safety, as the probability of an accident would increase largely if normal flight and ATC procedures would be maintained, to have large negative effects on capacity and costs, as airport capacity is reduced considerably and this typically leads to delays and associated cost increases, and to have negligible effects on environment, as the low visibility procedures do not increase noise or fuel burnt. As low visibility conditions may occur regularly (dependent on the location of the airport), this is an example of a disturbance with large effects and a high likelihood of occurrence.
- The disturbance "Track problem" refers to situations involving the radar track on the screen of a controller, such as track swaps, track drops and false plots. These are rare events, which typically occur for a limited time. If a controller identifies a radar track problem, the controller may ask pilots to report positions, to ask the pilots about potential problems with the radar transponder, and potentially to use non-radar procedures with larger separations if the situation maintains for a longer period. The strategy is assessed to have a small positive effect on safety, as situation awareness about the aircraft position is partly retained, to have small negative effects on capacity and costs, as the larger separation may lead to some reduction in capacity and increase in costs, and to have a negligible effect on environment.
- The disturbance "ATIS problem" refers to incorrect or not up-to-date information provided by the Automatic Terminal Information Service, which is a continuous broadcast of aeronautical information, such as weather information and special conditions at the airport. ATIS data being out-of-date is considered to occur regularly. The strategy of pilots is to ask controllers for the latest information if they recognize by a time stamp in the ATIS data that it is out of date. The strategy of controllers is to arrange an update of ATIS data. The strategy's effect on safety is assessed as small positive, especially for approach and landings operations. The effects on capacity, environment and costs are assessed as negligible.
- The disturbance "Allowance to deviate from normal procedure" refers to cases where controllers allow pilots to deviate from procedures. This is a situation occurring regularly and it was actually not considered a disturbance by the pilots and controllers in the workshop. The strategy is to coordinate well with pilots and other controllers, such that parties are well informed and

the situation is under control. The strategy's effect on safety is assessed to be negligible, as effective coordination between the parties involved can ensure that the situation is well under control. The effects on capacity and costs are assessed to be small positive, as the deviations from procedures are intended to temporarily work around potential problems. The effect on environment is assessed as negligible, as the deviations are typically done for efficiency reasons.

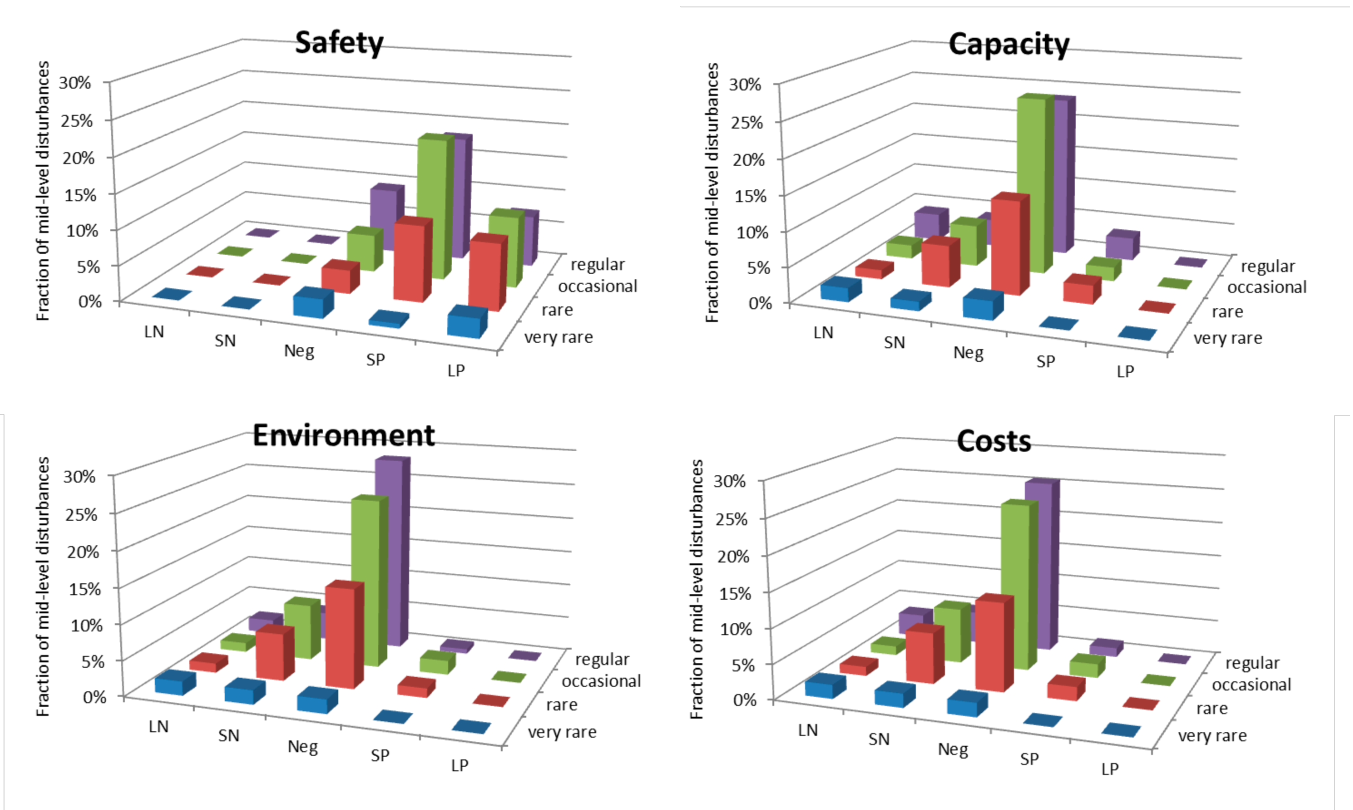


*Figure 3. Effects of strategies of pilots and controllers on the ATM KPAs safety, capacity, environment, and costs for dealing with disturbances. For each KPA, effect size (from LN to LP), and frequency (from very rare to regular), the fraction of associated mid-level disturbances is shown*

For each KPA, Figure 3 shows the fraction of mid-level disturbances per frequency category of the disturbance and per strategy effect category. For safety, the overall result is that the strategies have positive implications in about 79% of the mid-level disturbances and negligible effects for the remainder of the disturbances. Many of the positive safety implications are achieved for disturbances that occur occasionally or regularly. The results for the KPAs capacity, environment and costs in Figure 3 show that the strategies for dealing with disturbances have negligible effects for most disturbances (27-30%). The applied strategies may have negative effects on these KPAs for a considerable number of disturbances (64-68%), and only for relatively few disturbances the strategies have small positive effects (4-8%).

## 5.2 KPA EFFECTS OF STRATEGY CLUSTERS OF CONTROLLERS AND PILOTS

As a way to combine frequency of a mid-level disturbance and the size of the effect on a KPA we define the ranking in Table 6. Herein the most frequent disturbances with the largest effects on a key performance area rank highest. For each of the four key performance areas, rankings can be made with regard to positive or negative contributions of the strategies for dealing with the disturbances. As an example, Figure 4 shows the safety effects of the high-level strategies of air traffic controllers. It follows from this figure that the most prominent positive effects are due to the high-level strategies ATC-pilot interaction, Configuration management, and Tactical control cycle. Similar overviews can be obtained for the other KPAs.

*Table 6. Definition of a ranking for the combination of frequency and size of effects of strategies on key performance areas*

| Ranking | Frequency category | Effect category |
|---|---|---|
| P1 | Regular | Large positive |
| P2 | Regular | Small positive |
| P3 | Occasional | Large positive |
| P4 | Occasional | Small positive |
| P5 | Rare | Large positive |
| P6 | Rare | Small positive |
| P7 | Very rare | Large positive |
| P8 | Very rare | Small positive |
| Neg | Regular / Occasional / Rare / Very rare | Negligible |
| N8 | Very rare | Small negative |
| N7 | Very rare | Large negative |
| N6 | Rare | Small negative |
| N5 | Rare | Large negative |
| N4 | Occasional | Small negative |
| N3 | Occasional | Large negative |
| N2 | Regular | Small negative |
| N1 | Regular | Large negative |

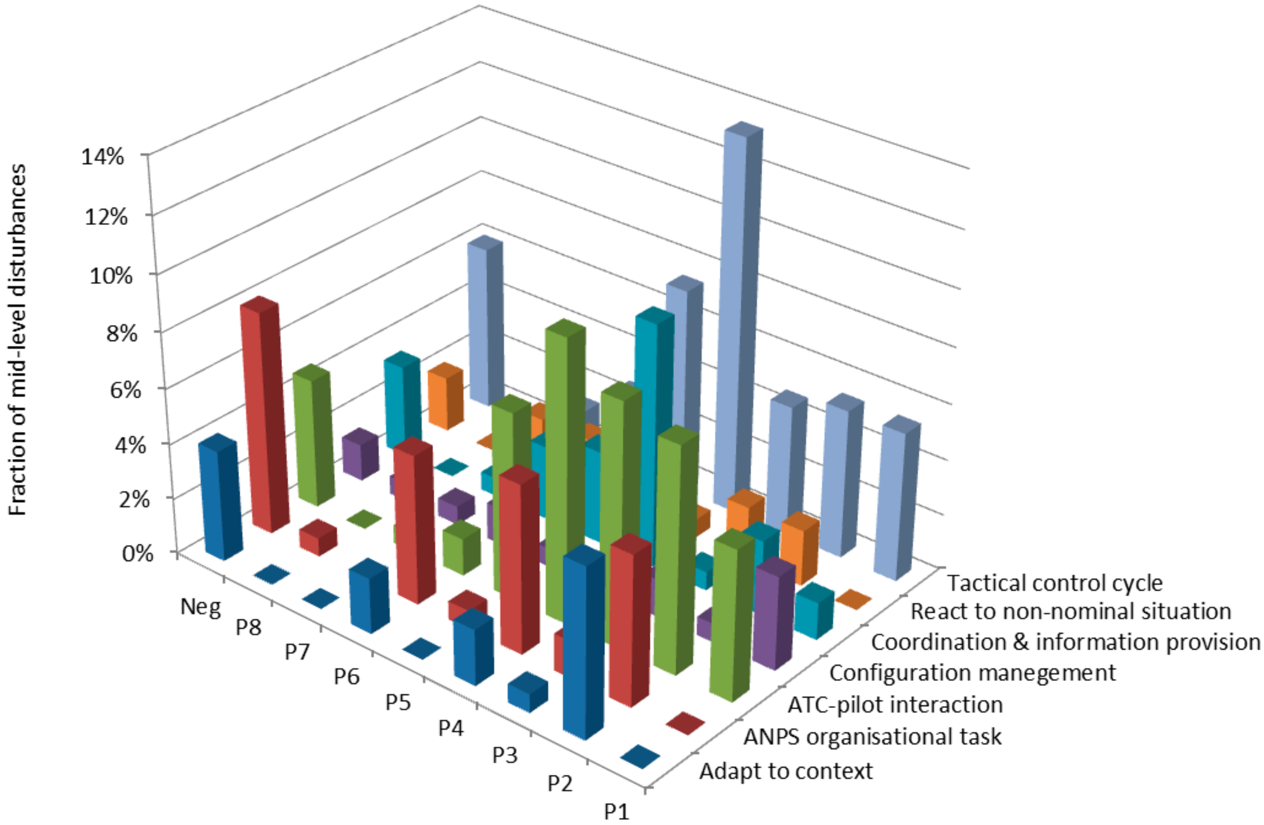


*Figure 4. The safety effects of high-level controller strategies using the effect categories of Table 6. (Categories N1 – N8 are not shown, since they are all empty.)*

Insights that have been achieved for high-level strategies of air traffic controllers on the basis of these types of results include the following. Similar types of insights can be achieved for the strategies of pilots.

- Adapt to context – The strategies of controllers to deal with differences between airlines, large workload, and situations lacking procedures have a positive or negligible effect on safety. For the other KPAs the effects are mostly negligible, but negative effects arise from strategies to deal with organisational problems with the ATC workforce, such as strikes, major illness, or an insufficient number of controllers.
- ANSP organisational task – The strategies concerning the ANSP organisation such as reporting of problems, safety management and training mostly have small or negligible effects on the KPAs.
- ATC-pilot interaction – The communication actions between controllers and pilots, such as providing instructions and information, or requesting information are applied a lot to deal with disturbances. These actions have a positive effect on safety. For instance, confusion about aircraft identity or the

contents of a clearance in the communication is assessed to occur regularly and it may have large safety effects. Common strategies in ATC-pilot interaction, such as effective use of readback or splitting up complex clearances can prevent such types of misunderstandings to progress. The effect on the other KPAs is often negligible, but in some contexts (e.g. reduced visibility) the information provision may be related to reduction in capacity and increase in costs.

- Configuration management – The strategies to adapt airspace or airport configurations in reaction to disturbances (e.g. weather conditions) have considerable positive effects on safety, but also may have considerable negative effects on capacity, environment and costs.
- Coordination & information provision – Coordination and information provision have considerable positive effects on safety. For instance, a controller may provide a wrong message or may not provide a message when needed, and another controller (e.g. planning controller) may remind/correct, such that further progression of the situation is prevented. The effects of the strategies on the other KPAs are often negligible and in some cases negative or positive. The largest negative effects are related to information provision about bad weather.
- React to non-nominal situations – The application of contingency and emergency procedures is assessed to have mostly positive effects on safety. For the other KPAs the effect is mostly negligible or negative, but no more than small negative for disturbances occurring occasionally.
- Tactical control cycle – Controller strategies for planning, monitoring, and interventions are at the core of the controller main task and they are applied for dealing with a large number of disturbances. The effects on safety are positive, up to the level of large positive effects for regularly occurring disturbances. The effects on the other KPAs vary depending on the context. The largest negative effects are associated with planning for winter conditions and applying separation criteria.

## 5.3 KPA EFFECTS FOR DISTURBANCE CLUSTERS

To achieve insight into the types of disturbances for which the strategies of pilots and controllers have largest implications, the KPA effects of the strategies have been associated with disturbances. As an example, Figure 5 shows the effects on safety strategies for dealing with the high-level disturbance categories. It follows from this figure that the most prominent positive safety implications arise from strategies to deal with bad weather situations and traffic relations. Similar overviews can be obtained for the other KPAs.

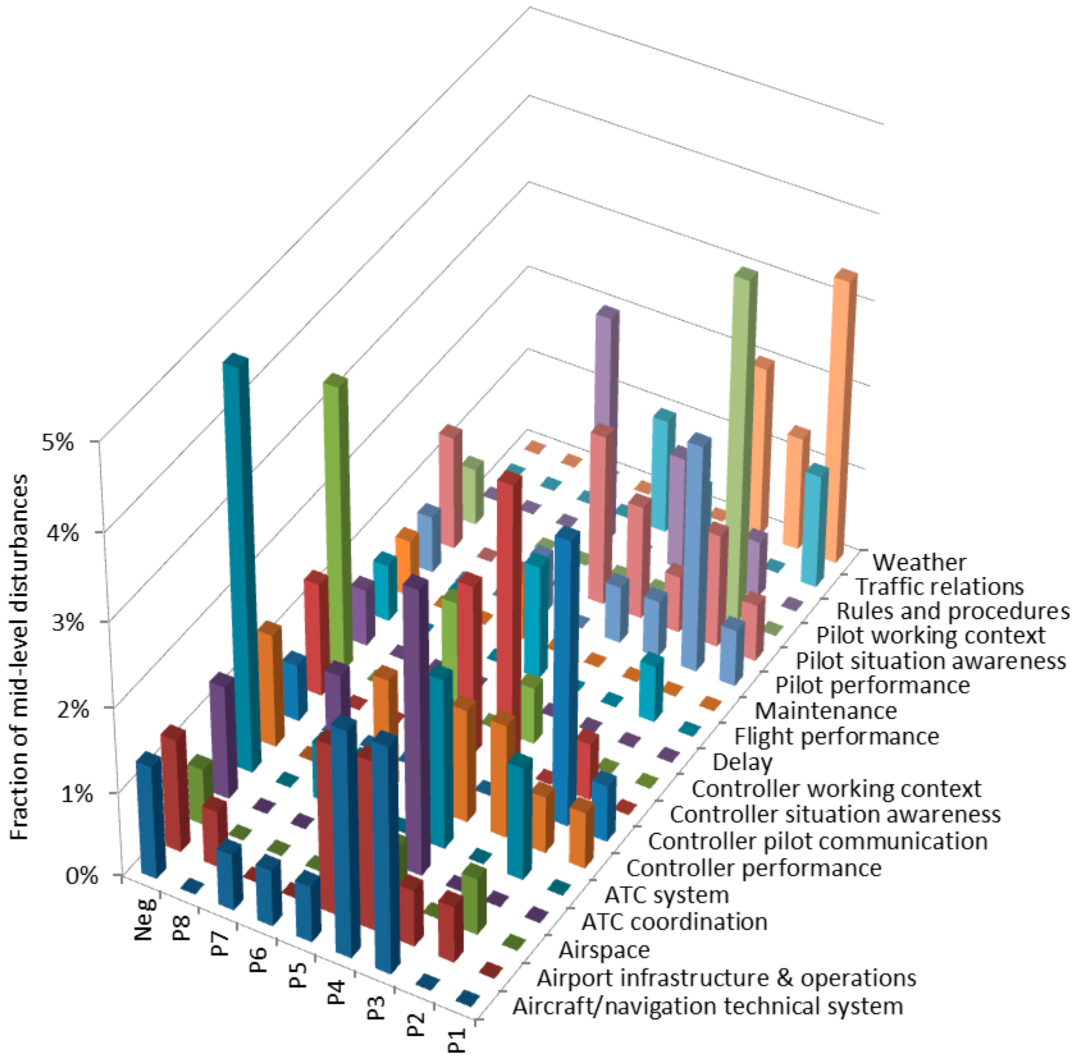


*Figure 5. The safety effects of pilot and controller strategies for dealing with high-level disturbance clusters using the effect categories of Table 6. (Categories N1 – N8 are not shown, since they are all empty.)*

Based on these results, the following insights have been achieved for selected high-level disturbance categories.

- Aircraft/navigation technical systems – These disturbances do not occur frequently or the effect of the strategy is considered negligible, such that the KPA rankings are limited. The largest effect is due to the occurrence of false or nuisance alerts, which may have a negative effect on environment and costs for the flight considered.
- Controller performance – Disturbances related to controller performance typically refer to some kind of error in the performance. The strategies are directed to detecting and correcting these errors, e.g. by own detection, via interaction with pilots, or via coordination with other controllers. Such

detection and correction mechanisms have important positive safety effects for regularly occurring disturbances, such as wrong or missing messages.

- Controller pilot communication – Disturbances affecting the communication between pilots and controllers are assessed to occur regularly. Strategies towards resolving misunderstandings in the controller pilot communication have positive safety effects, which are considered to be most prominent for proper understanding of the aircraft identity (e.g. call-sign confusion).
- Controller working context – The most important mid-level disturbance categories are Organisation & workforce (e.g. controller shortage, strikes, reorganisation), and Workload (e.g. large workload levels of controller). The strategy to reduce capacity may have considerable negative effects on the KPAs capacity, environment and cost-efficiency.
- Pilot performance – There are several mid-level disturbances in this category on pilot performance that may occur regularly (e.g. not precisely following the ATC clearance) and for which correcting strategies are important for flight safety.
- Pilot situation awareness – Situation awareness problems of pilots with regard to crew differences, flight routing and lack of knowledge of local procedures are considered to occur regularly and strategies to resolve these kinds of disturbances are considered important for flight safety.
- Pilot working context – Various disturbances in this category, such as fatigue, limited safety culture and workload problems, may occur regularly, and strategies for dealing with them are mostly focused on improving safety.
- Rules and procedures - These disturbances mostly do not occur frequently or the effect of the strategy is considered negligible, such that the KPA rankings are limited. Differences between procedures occur regularly, and the flight-preparation and pilot-controller communication strategies towards alleviating the potential misunderstandings are expected to have a positive effect on safety.
- Traffic relations – The disturbances in this category are at the core of air traffic control. The disturbances in the categories Aircraft speed differences, and Wake vortex separation occur regularly and the strategies for dealing with them have considerable positive effects on safety. The safety-capacity trade-off in wake vortex separation implies a negative effect on runway capacity.
- Weather – Weather-related disturbances, such as low visibility, winter conditions, strong wind, and thunderstorms are occurring regularly. Strategies for dealing with such weather conditions have a focus on flight safety and typically imply a considerable capacity reduction and potential negative implications for cost-efficiency and environment.

# 6 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 present-day air traffic operations. These disturbances have been identified in considerable number of 'pure brainstorming' sessions for the assessment of the safety of air traffic operations. Since the followed brainstorming guidelines prohibit analysis during the sessions, a wide diversity of disturbances has been identified, which may have effect on various KPAs. The set of disturbances addresses technical systems in aircraft and in the ATC system, performance of pilots and controllers, communication and coordination in ATM operations, weather, traffic relations, etc. Notwithstanding the size and variety of the set of identified disturbances, it is recognized that the disturbances are mostly focused on the sharp end of air traffic operations with pilots and air traffic controllers working as key operators. For a broader perspective on resilience of air traffic, additional disturbances affecting other parts of the organisation can be identified and studied, such as for airline operations control, maintenance and system engineering at airlines, ANSPs and airports, turn-around processes, flow management, and a variety of management processes at airlines, ANSPs and airports, including acquisition and development, resource management and safety management. In practical assessments typically a limited scope is considered, addressing particular operations and parts of the overall organisation, and the range of disturbances to be considered depends on this scope. The selection of the scope is delicate process in which it needs to be considered what sharp and blunt ends of the organisation have to be included to address the research questions underlying a resilience assessment. In addition to the scoping with regard to the organisational structure, the scope should address the range of key performance areas to be considered. As part of a resilience assessment, specific disturbances may be searched from the perspectives of the KPAs considered (cost-efficiency, environment, safety, etc.), such that a broader overall set of disturbances is attained. For the set of disturbances used in this paper, it implies that although the disturbances identified in the safety-focused brainstorms can be effectively analysed for effects on other KPAs, additional disturbances may be identified by specific searches from the perspectives of the KPAs. Such searches for disturbances may be done by brainstorming, or by studying literature for the KPAs and organisations considered. For instance, in addition to brainstorming, disturbances for the KPA safety may be gathered using safety assessments, accident/incident reports, accident/incident data reporting taxonomies (e.g. ICAO ADREP), or safety culture studies.

Notwithstanding the quest for a large and diverse set of disturbances as a basis for analysis of resilience, it should be realized that such a set of disturbances will never be complete. There will always be disturbances or particular combinations of disturbances that have not been experienced before or that have not been imagined in the analysis of a sociotechnical system. This understanding is at the core of the resilience engineering research field, which strives to sustaining operations under both expected and unexpected conditions, thus including disturbances that are not explicitly known in an analysis. Nevertheless, the analysis of resilience for a large and diverse set of (known) disturbances implies that many strategies for dealing with these disturbances are studied, which may also be useful for coping with other yet unknown disturbances. To increase the likelihood that strategies for known disturbances can be effective for unknown disturbances, the organisation should be able to apply the strategies generically. Whereas the work-as-done for a specific disturbance may be described in detail (i.e. at a low level of a strategy hierarchy), also the strategy at a higher level should be understood by people in the organisation, such that they are able to transform them to suitable low-level strategies when they encounter unknown disturbances that are similar to disturbances inside their disturbance-strategy knowledge base. The disturbances in such knowledge base should be sufficiently varied, such that operators are well able to find strategies for new disturbances using association with known disturbances.

The analysis in this study used disturbances as a starting point. This makes sense in the light of the definition of resilience as the ability of a system to adjust to changes and disturbances for sustaining required operations. Although the studied disturbances stemmed from safety studies, their purpose in the current analysis differs considerably from the application in traditional safety analyses. In traditional approaches (Safety-I, (Hollnagel et al., 2013)) disturbances are viewed as hazards, failures and errors, and analysis is focused on finding requirements that minimize their likelihood of occurrence and their potential consequences, e.g., requirements with regard to system dependability or human error. In the current study, disturbances are triggering points for description and analysis of the work-as-done for dealing with them in the sociotechnical system. As the occurrence frequency of the studied disturbances covers a broad range from very rare to regular, the assessed strategies of pilots and controllers includes everyday actions that are well known and practiced, as well as ways of working that are only known in theory and may require some improvisation to actually apply. This focus on a broad repertoire of actions is key within resilience engineering for arguing about effects on various KPAs in general and within the Safety-II view for arguing about safety implications in particular (Hollnagel et al., 2013).

As a way for effectively dealing with the large numbers of disturbances and strategies, we hierarchically clustered the disturbances and strategies at three levels, from low-level descriptions to high-level principles. This hierarchical way of clustering follows the clustering for resilience behaviour proposed in resilience markers framework of (Furniss et al., 2011), but it was extended to also include disturbances. The clustering was applied systematically to large sets of disturbances and strategies in ATM. The obtained disturbance and strategy clusters are not unique and other clustering techniques may be used to structure the disturbances and the approaches for dealing with them. Nevertheless, it was shown that it is feasible to effectively cluster large sets of disturbances and behaviour repertoires for operations in a complex socio-technical system.

The ways to detect and interpret disturbances and the coordination between human operators to attain a suitable strategy for coping with disturbances are important characteristics of resilience of a sociotechnical system. The results for the disturbances in ATM 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 first via a notification or an alert of a technical system (19%). Moreover, the analysis shows that there is always some level of coordination 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, of the cockpit crew, and between controllers and cockpit crew. The acquirement of the strategies is mostly based upon a combination of training and experience, indicating that the precise application of a strategy typically depends on the specific circumstances and cannot be based on standardized actions only. These results provide systematic support for the claims in resilience engineering about the key roles of human operators in ATM (Eurocontrol, 2009).

This paper provided a systematic approach for assessment of disturbances and related strategies using qualitative scales for frequencies and the effects on four KPAs in ATM. In particular, each mid-level disturbance was assessed using a 4-class scale (from very rare to regular) for its frequency and a 5-class scale (large negative to large positive) for the effects on a KPA of related strategies. Given this coarse scale, the large number of mid-level disturbances and the generality of the assessment, it is clear that the assessment results provide a rather rough overview of the frequencies and the implications of the strategies on the various KPAs. A more precise characterisation of the effects can be achieved in more detailed assessments, which take into account the specific context of the disturbances, and the potential interactions between a variety of disturbances.

The results show that the strategies have positive implications for safety 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 pilots and air traffic controllers when dealing with disturbances. 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. However, 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.

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). Such disturbances typically lead to considerable reductions in capacity, increase in delays, additional miles flown per flight, and decrease in cost-efficiency.

In conclusion, this paper has shown approaches for systematic structuring of large sets of disturbances and strategies for analysis of resilience of a complex sociotechnical system. In particular, this structuring has been achieved by hierarchical clustering of disturbances and strategies in ATM, by systematic characterization of key aspects of the strategies, by classification of effects on KPAs, and by combining these effects and disturbances frequency classes. We found that the majority of the disturbances in ATM are quite common and that the human roles in detection and interpretation of the disturbances, as well as in coordination to achieve a suitable strategy are important. Assessment of the implications of the strategies on ATM KPAs has shown that most strategies have positive safety effects, which may come at the expense of negative effects on other KPAs for a variety of disturbances. These results emphasize the important roles of pilots and controllers for dealing resiliently with disturbances in ATM and balancing the implications on the operational performance of their actions. Design principles for future more automatized ATM should take well into account these important human roles.

**Acknowledgements**
The research presented in this paper has been done mostly as part of the Resilience2050.eu project, funded by the Seventh Framework Programme of the European Commission, and for a minor extent as part of the MAREA project, funded by Eurocontrol on behalf of SESAR Joint Undertaking. We thank all participants of the interviews and the workshop.

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