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ORIGINAL ARTICLE

Uncertainty management in enroute air traffic control: a field study exploring controller strategies and requirements for automation

Sifra Corver[1] · **Gudela Grote**[2]

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Abstract The management of uncertainty is a critical aspect of current as well as future air traffic control operations. This study investigated: (1) sources of uncertainty in enroute air traffic control, (2) strategies that air traffic controllers adopt to cope with uncertainty, (3) the trade-offs and contingencies that influences the adoption of these uncertainties, and (4) the requirements for system design that support controllers in following these strategies. The data were collected using a field study in two enroute air traffic control centres, involving "over the shoulder" observation sessions, discussions with air traffic controllers, and document analysis. Three types of uncertainty coping strategies were identified: reducing uncertainty, acknowledging uncertainty, and increasing uncertainty. The RAWFS heuristic (Lipshitz and Strauss in Organ Behav Hum Decis Process 69:149–163, 1997) and anticipatory thinking (Klein et al. in Anticipatory thinking, Proceedings of the eighth international NDM conference, Pacific Grove, CA, 2007) were used to identify reduction and acknowledgement strategies. Recent suggestions by Grote (Saf Sci 71:71–79, 2015) were used to further explore strategies that increase uncertainty. The study presents a new framework for the classification of uncertainties in enroute air traffic control and identified the uncertainty management strategies and underlying tactics, in context of contingencies and trade-offs between operational goals. The results showed that controllers, in addition to *reducing* and *acknowledging* uncertainty, may deliberately *increase* uncertainty in order to increase flexibility for other actors in the system to meet their operational goals. The study describes new tactics for acknowledging and increasing uncertainty. The findings were summarized in the air traffic controller complexity and uncertainty management model. Additionally, the results bring to light system design recommendations that allow controllers to follow these different coping strategies, including (1) the design of alerts, (2) the transparency of prediction tools, and (3) system flexibility as a requirement for acknowledging and increasing uncertainty. The results are particularly important as uncertainty is likely to increase in future operations of enroute air traffic control, requiring automation support for controllers. Implications for future air traffic management scenarios as envisioned within the SESAR Joint Undertaking (SESAR JU in European ATM Master Plan, 2 eds, 2012) and NextGen (FAA in FAA's NextGen implementation plan, 2014) operational concepts are discussed.

Keywords Uncertainty management · Coping with uncertainty · Air traffic control · Adaptive strategies · System design · Naturalistic decision-making

1 Introduction

Air traffic management is a highly regulated industry, which aims at *minimizing uncertainties* (c.f. Grote 2004, 2009) through airspace design, standardized procedures (e.g. communication phraseology, standard routings), and coordination agreements between Air Navigation Service Providers, in order to manage risks and increase the predictability of operations. However, these efforts do not eliminate uncertainty from air traffic control operations.

✉ Sifra Corver
sifra.corver@skyguide.ch

[1] Skyguide, 8602 Wangen bei Dübendorf, Switzerland

[2] Department of Management, Technology and Economics, ETH Zürich, 8092 Zurich, Switzerland

Rather, uncertainty is considered a fundamental feature of air traffic control operations, as the predictability of the traffic is highly dependent on operational disturbances such as environmental conditions, and data required for decision-making may be incomplete, unreliable, ambiguous, or be subject to change at a later stage (Averty et al. 2008). Uncertainty may therefore negatively affect the controller's ability make optimal decisions and to plan future actions. Uncertainty can thus be defined as a "sense of doubt that blocks or delays action" (Lipshitz and Strauss 1997, p. 150). For example, winds and aircraft' engine parameter settings may cause variability of aircraft performance, which, in turn, may cause unreliable traffic conflict predictions (e.g. Averty et al. 2008; Cummings and Tsonis 2006). Uncertainty therefore may generate challenges to develop effective traffic solutions to solve a traffic conflict. Furthermore, thunderstorms and turbulence may create uncertainty concerning the availability of airspace (flight levels and traffic routes) and pilots' preferred trajectory through the sector, affecting controller's ability to develop strategic traffic plans. Therefore, the management of uncertainty is an important aspect of controllers' task work strategies (Malakis et al. 2010).

According to the RAWFS heuristic, which stands for *Reduction, Assumption-based reasoning, Weighing pros and cons, Forestalling,* and *Suppression*, decision-makers cope with uncertainty by adopting two types of coping mechanisms: *reducing* uncertainty and *acknowledging* uncertainty (Lipshitz and Strauss 1997). While *reduction* strategies aim to decrease uncertainty, by searching for additional information or engaging in assumption-based reasoning, *acknowledgement* strategies include approaches that accept uncertainty by taking it into account rather than reducing it (Lipshitz and Strauss 1997), for example, by weighing the pros and cons between options, adapting plans, and developing backup plans. The acknowledgement of uncertainty may take place when uncertainty cannot be (further) reduced or when this is too costly in terms of available resources or time (Lipshitz and Strauss 1997). Several recent studies have shown that the RAWFS heuristic is also successful in explaining how decision-makers cope with uncertainties in team context, such as firefighting teams (Lipshitz et al. 2007) and hostage-negotiating police teams (Van den Heuvel et al. 2014).

In addition to the RAWFS heuristic, several other naturalistic decision-making theories have shed light on how decision-makers create an understanding of the situation during highly complex, dynamic, and uncertain conditions. *Anticipatory thinking* (Klein et al. 2007), based on *sensemaking* (Weick 1995), describes various uncertainty-*reduction* strategies that support decision-makers to build an understanding of their operational environment through selective attention and detection of warning signals, enabling the anticipation of threats in the environment (Klein et al. 2006a, 2007). A related theory is the data/frame theory of *sensemaking* (Klein et al. 2006b), which describes how decision-makers establish a mental picture of the situation by constructing and elaborating a "frame", and by questioning and "reframing" a frame when new information is inconsistent with the existing frame (Klein et al. 2006b). Although the data/frame theory primarily describes how decision-makers *reduce* uncertainty, the model has some overlap with *acknowledging* uncertainty, as it not only explains how decision-makers detect frames, but also how they respond by adapting frames, thus having some commonality with other decision-making and planning models (Malakis and Kontogiannis 2013). The data/frame theory of sensemaking shows similarities with the common frame of reference framework (Hoc and Carlier 2002), which illustrates the cognitive processes that support the sharing of tasks between human controllers in Air Traffic Control.

Even though uncertainty is inherent to air traffic control operations (Averty et al. 2008), surprisingly few studies have investigated uncertainty management in air traffic control operations. Two recent studies (Kontogiannis and Malakis 2013; Malakis and Kontogiannis 2014) have illustrated how air traffic controllers (Tower Control) reduce uncertainty through (shared) *sensemaking* using the data/frame theory (Klein et al. 2006b). Furthermore, Malakis et al. (2010) have successfully illustrated how enroute air traffic controllers reduce and acknowledge uncertainty using the R/M Model (Cohen et al. 1996). However, various questions have remained unanswered. First, there is no comprehensive overview or classification of the various sources of uncertainty that may impact controllers. Such a classification is important as different sources of uncertainty may have different impacts on operations, and may require different uncertainty management strategies by air traffic controllers. Second, although recent studies have provided a good amount of insight into how controllers *reduce* uncertainty, less is known about the variety of strategies that controllers adopt to *acknowledge* uncertainty. In particular in complex systems with high demands for flexibility to manage operational disturbances, acknowledging uncertainty is preferred above reducing uncertainty, as increasing predictability may not be feasible or preferred. More recently, researchers have additionally argued that, in some situations, uncertainty may actually be preferred, as it allows flexibility and generates options to manage risks, suggesting that decision-makers may also adopt strategies that *increase* uncertainty (Grote 2015). However, whether controllers similarly adopt such strategies, and when the adoption of such strategies is preferred, has remained, up to now, unexplored.

Uncertainty management strategies may also reduce the complexity of the (traffic) situation. Coping with uncertainty therefore cannot be studied without taking into account the interplay between traffic complexity and uncertainty. Traffic complexity refers to the level of difficulty in managing the traffic, generated by flight characteristics of individual aircraft and interactions between pairs of aircraft, such as traffic conflicts (Djokic et al. 2010). Adapting traffic plans as a response to uncertainty (e.g. adverse weather) often involve changes to the trajectory of an aircraft, thus automatically reducing the complexity of the traffic at the same time. This means that although developing traffic solutions may be a direct response to uncertainty, these strategies also reduce complexity because the traffic situation is altered. Similarly, traffic plans can be used primarily with the aim of reducing complexity (e.g. resolving traffic conflicts regardless of the level of uncertainty involved in the conflict) but will, of course, indirectly also acknowledge and subsequently reduce uncertainty because uncertainty related to the probability of a possible future traffic conflict is removed. We will therefore focus on distinguishing between strategies that are aimed at managing uncertainty, complexity, or both. Third, although much is known about the trade-offs related to managing traffic complexity (e.g. Kirwan and Flynn 2002; Kontogiannis and Malakis 2013), previous studies have not provided much insight into how *contingency factors*, such as *operational constraints* and *trade-offs between operational goals,* may determine the favourability of uncertainty coping strategies. Finally, as little is known about the *requirements for automation* that support controllers in managing uncertainty, we aim to identify the requirements for system design and automated functions (e.g. radar display, information systems, and controller support tools) that provide optimal support to controllers in reducing, acknowledging, and increasing uncertainty. Understanding the system requirements that support controllers in managing uncertainty is particularly important, as uncertainty, for example, generated by adverse weather, generates additional workload for controllers (Neal et al. 2014). A better understanding how the operational system can support controllers in managing uncertainty may therefore also benefit efficiency and safety of operations. Therefore, we aim to advance the understanding of how controllers manage uncertainty in enroute air traffic control by answering the following questions:

1. What are the sources of uncertainties in air traffic control, and what are the action requirements they generate for air traffic controllers?
2. What are the tactics and underlying strategies used by air traffic controllers when deciding to reduce, acknowledge, or increase uncertainty and how are they distinguished from strategies aimed at resolving (traffic) complexity?
3. What operational constraints and trade-offs influence the adoption of these strategies?
4. What are the requirements for system design to support controllers in following different strategies for uncertainty management?

This paper is structured as follows: first, we provide a theoretical background discussing theories and frameworks of uncertainty management strategies. Second, we provide an overview of the *action requirements*, generated by different *sources* of uncertainty in enroute air traffic control. Third, we identify the strategies that controllers adopt to reduce, acknowledge, or increase uncertainty, based on the theories and frameworks as discussed. Fourth, we discuss the *contingency factors* that influence controller preferences with respect to these coping strategies. Fifth, we discuss the results with respect to *automation requirements*, which support controllers in managing uncertainty based on the identified strategies. Finally, we discuss the implications of our study for future air traffic management operations as envisioned in the SESAR Joint Undertaking (SESAR JU 2012) and NextGen (FAA 2014) operational concept.

2 Theoretical background

This section reviews existing literature that discusses the classification of uncertainty, uncertainty management strategies, and how automation may support operators with effectively managing uncertainty.

2.1 Sources of uncertainty

Uncertainty can be classified into three different types (Lipshitz and Strauss 1997). First of all, uncertainty may originate from a *lack of information* (Lipshitz and Strauss 1997), i.e. information is missing, partially missing, or unreliable. Information may be unreliable because the source (either a system, or human operator) cannot be relied upon, or because the data required for decision-making (e.g. used by automated systems such as conflict detection tools) lack precision (Hansson 1996). Second, according to Lipshitz and Strauss (1997), uncertainty may also emanate from an *inadequate understanding* (i.e. inability to understand or comprehend information due to ambiguity, equivocality, or novelty). Third, uncertainty may also stem from the inability to make a decision due to *undifferentiated alternatives*, meaning that decision-makers cannot differentiate alternatives because predicted outcomes are equally (un)preferable (Lipshitz and Strauss 1997), despite the availability of information and the ability to understand the information. Furthermore, Lipshitz and Strauss (1997) argue that uncertainty can be classified in terms of its *source* (i.e. what is causing uncertainty) and the *issue* arising from uncertainty (i.e. what the decision-maker is uncertain about). From this point onwards, we will refer to issue as *action requirement*. The distinction between sources of uncertainty and action requirement is important, as one sources of uncertainty may generate more than one issue for decision-makers, thus requiring different management strategies and different demands on the automation.

2.2 Uncertainty management strategies

Various theories and frameworks exist that describe how decision-makers manage uncertainty. According to the RAWFS heuristic (Lipshitz and Strauss 1997), decision-makers *reduce* uncertainty through "reduction" and "assumption-based reasoning". Tactics within "reduction" include, but are not limited to *searching for additional information* (e.g. asking for advice or opinions) or *relying on (in)formal rules* (e.g. procedures, shared working methods). "Assumption-based reasoning" includes tactics that explain how decision-makers "fill the gaps of missing knowledge", by using *assumptions* to reduce uncertainty; that is, how they create understanding when information is missing by using their expertise and previous experience.

Another strategy, proposed by Klein et al. (2007), *anticipatory thinking,* explains how decision-makers reduce uncertainty through sensemaking, by selecting attention and detecting possible threats or problems during recognition-primed decision-making tasks. Anticipatory thinking relies on *mental simulation* as a cognitive process and allows decision-makers to detect problems in planned or anticipated responses, a process that is essential for planning and replanning (Klein et al. 2007). Anticipatory thinking supports *vigilance* and prevents *fixating*. Three different types of anticipatory thinking are pattern recognition, trajectory tracking, and convergence. *Pattern recognition* refers to how decision-makers detect patterns and how they compare these patterns with stored patterns in order to detect abnormalities and deviations as cues for intervention (Klein et al. 2007). *Trajectory tracking* refers to extrapolating situations to future states and actively comparing observed future states and required future states in order to identify proactive responses (Klein et al. 2007). Trajectory tracking is similar to task monitoring. According to Osman (2010), task monitoring reduces uncertainty by testing predictions about the future state and using the feedback to update a decision-maker's understanding about the environment. *Convergence* refers to the cognitive process of creating connections between events in order to understand how these events interrelate (Klein et al. 2007).

Two main strategies for *acknowledging* uncertainty are identified in the RAWFS heuristic: "weighing pros and cons" and "forestalling". *Weighing pros and cons* is a strategy that controllers adopt when comparing or choosing between competing options, whereas *forestalling* involves strategies that aim to improve readiness (e.g. buffering resources or creating *backup* or *contingency* plans) in order to prepare for adverse outcomes and to avoid irreversible action (Lipshitz and Strauss 1997). Contingency plans have been recognized as an important element of responding to evolving uncertainty in air traffic control operations (Malakis et al. 2010). Additionally, Kontogiannis (2010) acknowledged adaptive planning as an important strategy in the context of uncertainty. Adaptive planning is different from forestalling as it focusses on changing plans that are in progress (and thus already have been implemented), whereas forestalling refers to the development of new plans in order to improve readiness in case of unexpected outcomes.

Grote (2015) suggests that *increasing* uncertainty may also be a viable option, as the increase of uncertainty can add adaptive capacity and increase flexibility, for instance, by avoiding premature convergence in decision-making, as a strategy to reduce risk. Increasing uncertainty may happen, for instance, by deliberately introducing doubts or new options in decision-making or by adopting "flexible rules" that allow degrees of freedom, which initially raise rather than reduce uncertainty for the decision-maker. Increasing uncertainty may be particularly successful in high-reliability organizations (Weick 1995), including air traffic management, where flexibility needs to be maintained in order to successfully manage expected, as well as unexpected disturbances in operations. The ability to increase uncertainty is an important strategy in order to ensure resilience of operations, in particular when flexibility is preferred due to interdependencies of tactical plans and complexity of operations (Grote 2015). Taking up this proposal, we were interested to see whether controllers employ strategies to increase uncertainty and, if so, under what conditions.

2.3 Automation requirements

Air traffic control be regarded as a complex human–machine system, or "joint cognitive system" (Hollnagel and Woods 1983), consisting of human agents and automation, that are designed to allow human–machine cooperation (HMC; Hoc 1996). The automation in air traffic control consists of various automated functions and is presented to the controller on the human–machine interfaces (HMI) of the controller's working position. The automated functions include controller support tools, and other functions, that aid controllers with various cognitive and collaborative tasks, such as coordination and traffic conflict detection, prediction, and analysis.

To date, most research has focused on how uncertainty negatively influences the reliability of automation, raising various issues with respect to *trust* and *vigilance* of decision-makers, such as controllers (e.g. Parasuraman and Manzey 2010; Parasuraman and Wickens 2008). Too high reliability, on the other hand, can be a threat to anticipatory thinking as it may increase the risk on *fixation* (De Keyser and Woods 1990) and reduce vigilance, also referred to as *complacency* (Parasuraman and Manzey 2010; Parasuraman and Wickens 2008) due to passivity induced by automation (Klein et al. 2007). Other authors have argued that automation may also have limitations with respect to conflict-resolution support due to the inability of automation to take into account the naturalistic decision-making models, including human trade-offs and the subjective evaluation of possible outcomes (Cummings and Tsonis 2006; Parasuraman and Wickens 2008), which may become particularly relevant during conditions of uncertainty. Researchers have also stressed the challenges of current automation to integrate uncertainty into algorithmic models of controller conflict detection tools (c.f. Knorr and Walter 2011), resulting in discussions on how to display predictions generated by unreliable predictions from algorithmic conflict detection and analysis tools. In an attempt to solve this issue, Nicholls (2001) discussed various ways of graphically *presenting* and *visualizing* uncertainty on radar displays for air traffic control operations. We took these discussions as a starting point and investigated how automation can support controllers' coping strategies, and how uncertain information is graphically presented and visualized.

3 Methods

We chose an ethnographic approach by conducting a field study in two enroute area control centres (ACC). Field studies in naturalistic or real settings are the recommended approach for studying (macro) cognitive functions (such as decision-maker strategies) in complex socio-technical systems and high-risk teams, as these functions are often highly dependent on various environmental factors, including dynamic task demands and contingencies, which can only be captured in real operational settings (Hutchins 1995; Xiao 2005). Field studies are therefore considered the recommended approach for studying uncertainty (Klein et al. 2003; Lipshitz et al. 2001) and have been used to study a wide range of cognitive and collaborative processes in ATC operations (c.f. Mackay 1999; Sharples et al. 2007; Soraji et al. 2012).

3.1 The setting

In enroute air traffic control (Enroute ATC), airspace is divided into airspace blocks, referred to as airspace sectors, which are defined by a geographical boundary and a lowest and highest flight level. They are managed by a team of two air traffic controllers: a *radar executive* and a *radar planner,* sitting behind separate radar screen, which is part of their controller working position (Fig. 1). The main goal of the air traffic control team is to provide safe and efficient air navigation service to aircraft within their sector by optimizing traffic flows

Fig. 1 Controller working position with radar executive and radar planner

Fig. 2 Electronic coordination tool

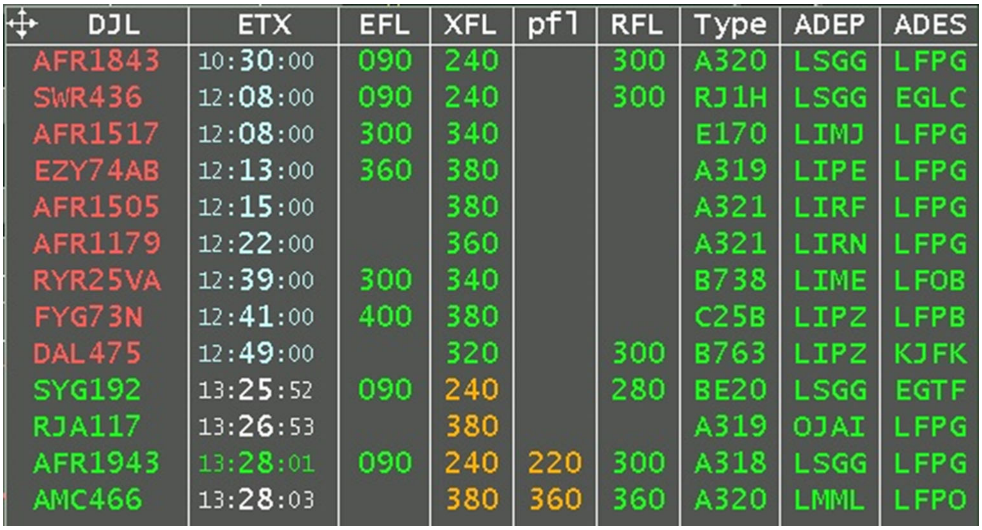
and maintaining separation between aircraft (1000 feet vertically due to reduced separation minima and five nautical miles horizontally), according to the standards mandated by the International Civil Aviation Organization (ICAO 2007).

The radar executive and the radar planner are responsible for different tasks within the team. The radar executive is in charge of identifying aircraft and giving clearances (e.g. flight level or route instructions) to the aircraft, as well as detecting, identifying, and solving possible traffic conflicts within the sector in a *tactical* timeframe, which we refer to as *tactical traffic solutions*. The radar planner is responsible for solving possible future traffic conflicts in a *strategic* timeframe with neighbouring sectors, before the aircraft enter the sector, which we refer to as *strategic traffic solutions*, by coordinating tactical traffic solutions with neighbouring sectors. Although the radar planner and the radar executive have different responsibilities, they share high levels of task interdependency: the radar planner needs to be continuously ahead of the needs and preferences of the radar executive. In addition, the radar planner provides support to the radar executive in tactical conflict management and monitoring whenever backup support is required, thereby improving the workload balance within the team.

At the time of observation, both ACCs were equipped with different levels of automation. In the ZRH ACC, controllers were supported with planning and measuring tools only. In the GVA ACC, however, controllers were supported with various controller support tools to facilitate their work, including electronic coordination (Fig. 2), medium-term conflict detection (MTCD) tools (Figs. 3, 4, 5), analysis support tools (Figs. 6, 7), and monitoring aids (Fig. 8), in addition to planning and measuring tools. The differences between the two ACCs in terms of availability of controller support tools are shown in Table 1. A full overview and description of the controller support tools are presented in “Appendix”.

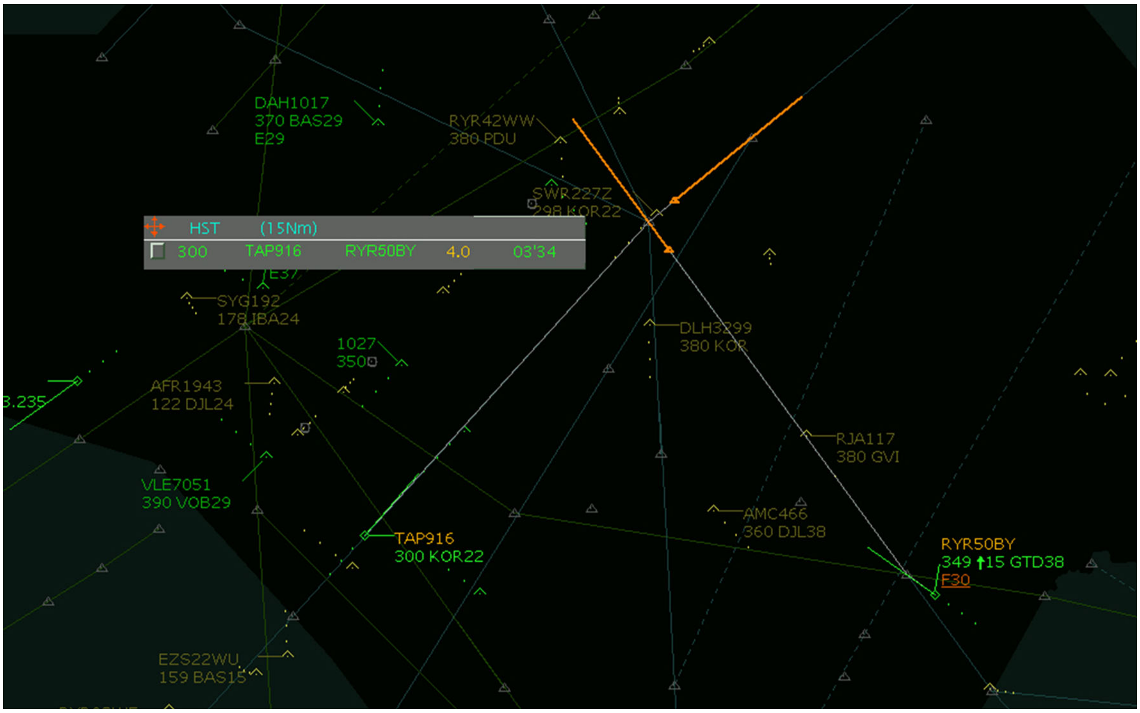
3.2 The procedure

The data were collected in two enroute area control centres (ACC’s) during two field studies. Field study 1 was conducted at the Zurich Area Control Center (ZRH ACC) in lower and upper airspace sectors, covering altitudes between 11,000 and 66,000 feet (FL110-660). Field study 2 was conducted at the upper enroute sectors of the Geneva Area Control Center (GVA ACC), covering altitudes between 25,000 and 66,000 feet (FL250-660). Before data collection, a documentation study, including the study of procedure and user manuals, was conducted in order to gain an understanding of the overall system, the human–machine interface, as well as operational rules and procedures.



DJL	ETX	EFL	XFL	pfl	RFL	Type	ADEP	ADES
AFR1843	10:30:00	090	240		300	A320	LSGG	LFPG
SWR436	12:08:00	090	240		300	RJ1H	LSGG	EGLC
AFR1517	12:08:00	300	340			E170	LIMJ	LFPG
EZY74AB	12:13:00	360	380			A319	LIPE	LFPG
AFR1505	12:15:00		380			A321	LIRF	LFPG
AFR1179	12:22:00		360			A321	LIRN	LFPG
RYR25VA	12:39:00	300	340			B738	LIME	LFOB
FYG73N	12:41:00	400	380			C25B	LIPZ	LFPB
DAL475	12:49:00		320		300	B763	LIPZ	KJFK
SYG192	13:25:52	090	240		280	BE20	LSGG	EGTF
RJA117	13:26:53		380			A319	OJAI	LFPG
AFR1943	13:28:01	090	240	220	300	A318	LSGG	LFPG
AMC466	13:28:03		380	360	360	A320	LMML	LFPO

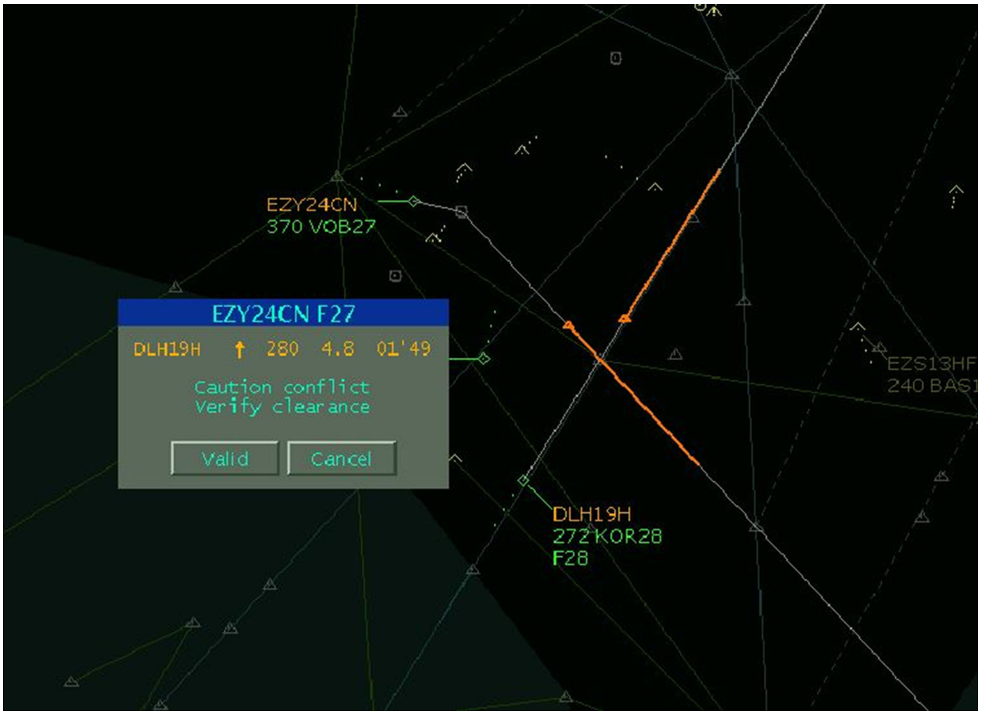
Fig. 3 Exit Conditions Assistance Tool (ECAT; simulated)



HST (15Nm)

☐ 300 TAP916 RYR50BY 4.0 03'34

Fig. 4 Horizontal Scanning Tool (HST; simulated)



EZY24CN F27

DLH19H ↑ 280 4.8 01'49

Caution conflict
Verify clearance

Fig. 5 Dynamic Scanning Tool (DST; simulated)

The methods used within this field study included:

- "Over the shoulder" observations of air traffic controllers, supported by detailed field notes;
- Discussions with controllers during breaks and after shifts;
- Discussions with system engineers during various (informal) meetings.
- Document analysis (study of operational procedures, simulation studies, and evaluation reports of operational concepts).

Fig. 6 Crossing Tool (simulated)

3.3 Data collection and analysis

The observations were conducted by the first author of this study. Air traffic controllers were observed for a total duration of 80 h in field study 1 and for a duration of 50 h in field study 2. In total, more than 86 different controllers were observed. Both radar executive and radar planner positions were observed. All controllers were experienced controllers with a valid endorsement. Age and experience were not recorded to respect the anonymity of the controllers. During the “over the shoulder” observations, field notes were collected based on observations and elaborated with comments made by the controllers and the discussions during and after the shifts. Drawings and sketches recorded specific traffic situations. The observations focused on understanding the sources of uncertainty and the cognitive and collaborative strategies controller adopted to manage uncertainty. Cognitive strategies were identified by observing the interactions with the human–machine interface (HMI), whereas collaborative strategies, shared between controllers and/or pilots, could be identified by observing “silent” coordination through the HMI as well as overhearing voice communication. Furthermore, discussions with controllers and system engineers gained us a further understanding how the automated system, including controller support tools, supported the controllers in managing complexity and/or uncertainty.

After data collection, the notes were digitalized and analysed by the first author. Drawings of traffic situations were photographed and added to the digital notes. Subsequently, the notes were analysed by collecting all the statements and observations reflecting the sources of uncertainty, which were then later grouped according to the action requirements (issues) they generated for controllers. We then continued by identifying all the uncertainty management strategies in the data and allocated them according to the three main strategies of uncertainty management. Finally, we created an overview of all the automated functions and controller support tools and analysed how and when controllers used them and how they supported uncertainty management strategies.

4 Results

The results are reported in four different sections: (1) sources of uncertainties, grouped by the action requirements, (2) the strategies and underlying tactics that controllers adopted in response to these uncertainties, (3) the *operational constraints* that influenced the adoption of these strategies, and (4) how the automated system supported the controllers in adopting strategies to manage uncertainty.

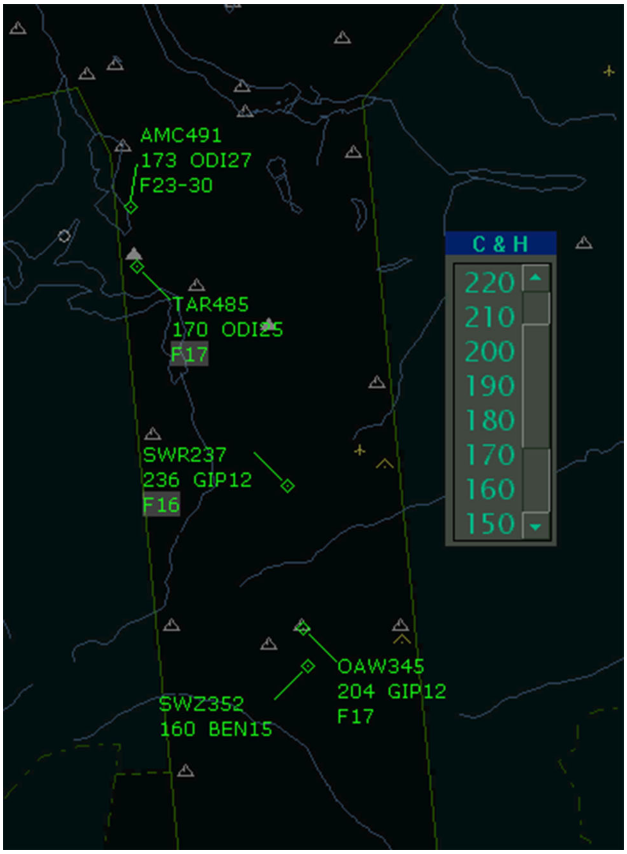


Fig. 7 Click and Hold Tool (simulated)

Fig. 8 Cleared Adherence Monitoring Tool (simulated)

4.1 Sources of uncertainty

From the analysis, four categories of uncertainty emerged: (1) system information uncertainty; (2) procedural uncertainty; (3) traffic situation uncertainty; and (4) trajectory uncertainty (see Table 2).

The results showed that all the action requirements (issues) that controllers needed to manage as a result of uncertainty could be classified in four different categories of uncertainty. First, *system information uncertainty* pertains to situations in which information regarding the status or integrity of elements in the operational system, including airspace sectors, airspace users, and automation (services), may be missing, ambiguous, incomplete, conflicting, or unreliable. The second category of uncertainty refers to *procedural uncertainty*, which exists when there is doubt amongst the controllers concerning the procedural course of action. The third category of uncertainty refers to the *traffic situation*, as a result of the predictability of a traffic conflict (i.e. anticipated minimum separation and time until minimum separation) or the ability of an aircraft to reach its agreed entry or exit conditions. Finally, controllers also experienced uncertainty concerning an aircraft's preferred *trajectory* through the sector. The results, as presented in Table 2, showed that a single action requirement (e.g. uncertainty about a potential traffic conflict in the sector) may be caused by various *sources* of uncertainty (e.g. aircraft performance variability as a result of engine parameter settings or winds). The results also show that a single source of uncertainty can generate different action requirements for the controllers. For example, wind may generate uncertainty about possible future conflicts in the sector as well as deviations from trajectories. Furthermore, the results showed that each action requirement was linked to different *types* of uncertainty, i.e. lacking information (e.g. aircraft trajectory through the sector, as a result of missing flight plan data), inadequate understanding (e.g. ambiguous aircraft intentions, as a result of thunderstorms), or undifferentiated alternatives (e.g. optimal intervention strategy, as a result of the non-conformance of an aircraft).

4.2 Uncertainty management strategies

This section discusses the uncertainty management strategies that were identified. The strategies include cognitive as well as collaborative strategies.

4.2.1 Reducing uncertainty

The *reduction* strategies and underlying tactics are described and summarized in Table 3.

4.2.1.1 Collecting information An important strategy of controllers to reduce uncertainty is to *collect (additional) information*; therefore, controllers often consulted and compared different information systems. When information systems provided conflicting or missing system information, controllers would call other sectors or the military to obtain more accurate or up-to-date information. This strategy was most often observed when *information uncertainty* was present. Often, while controllers were

Table 1 Controller support tools in Zurich ACC and Geneva ACC

Controller support tools at Zurich ACC (ZRH)	Controller support tools at Geneva ACC (GVA)
Phone coordination for coordination with other sectors, within and outside ZRH ACC	*Phone coordination* for coordination with other sectors outside GVA ACC *Electronic coordination tools* (E-coordination, Fig. 2), which support the exchange of coordination proposals between the upper sectors of GVA ACC controllers with coordination of transfer conditions for an aircraft, such as specific flight level, routing, heading, or speed
Conflict detection not supported by automation	*Medium-term conflict detection tools (MTCD)*, which support controllers with the detection and analysis of exit conflicts (exit conditions assistance tool, ECAT, Fig. 3), horizontal crossings (horizontal scanning tool, HST, Fig. 4), and the validation of an entered clearance (dynamic scanning tool, DST, Fig. 5)
Conflict analysis not supported by automation	*Analysis support tools*, which support controllers with the analysis of a crossing of two aircraft on the same flight level (crossing tool, Fig. 6) and analysis of available flight levels (click and hold tool, Fig. 7)
Planning and measuring tools (speed vectors, planning tool, and measuring tool)	Planning and measuring tools (speed vectors, planning tool, and measuring tool).
Monitoring tasks not supported by automation	*Monitoring tools*, which support controllers in detecting aircraft deviations, including a lateral deviation (route adherence monitoring function, RAM) or a vertical deviation (cleared level adherence monitoring, CLAM, Fig. 8)

searching for additional information, they were simultaneously generating possible traffic solutions, which suggests that the reduction and acknowledgement of uncertainty within teams may take place in parallel. For example, controllers deferred traffic plans requiring military airspace until conflicting information related to the availability of airspace was resolved, while at the same time developing traffic plans that avoided the use of military airspace in case a direct routing using military airspace was not possible.

4.2.1.2 Informal rules of conduct Another important reduction strategy observed for controllers was to rely on *(in)formal rules of conduct*. We found that this strategy seemed to be particularly associated with *procedural uncertainty*: controllers preferred to do what is "common sense" or "do what is safe" in cases where: (1) the applicable procedure was unknown, or (2) the applicable procedure was known, but the situation would not allow the applicable procedure to be followed due to deviation from procedures arising from other actors in the system. For example, during one session, controllers identified that the military occupied more airspace than usual for military exercises. Instead of directly reducing uncertainty by searching for procedural information, the radar executive preferred to reduce uncertainty by relying on informal rules of conduct by doing "what is safe", immediately followed by acknowledging uncertainty by adapting traffic plans to safely separate the traffic.

4.2.1.3 Anticipatory thinking We could also identify anticipatory thinking strategies during conditions of uncertainty: controllers continuously employed anticipatory thinking strategies, in particular when faced with uncertainty related to the *traffic situation* (e.g. traffic conflicts) and the *future (preferred) trajectory of an aircraft* through the sector. Controllers used pattern detection, by using visual cues to infer a need for intervention by comparing observed patterns with stored patterns. For example, controllers detected an aircraft deviating from routing by comparing the observed situation with his/her expectations (i.e. the controller's stored patterns about the planned route as well as anticipated deviations based on how winds impact aircraft deviations from routings). *Trajectory tracking*, which refers to monitoring the progress of one or more aircraft through the sector, was typically observed in case of a traffic conflict or anticipated nonconformance of exit or entry conditions. For example, controllers estimated the minimum separation and the time until the minimum separation would be reached by *extrapolating* the speed vectors of the aircraft in order to visualize the future position of the aircraft, as well as the expected altitude of the aircraft. Finally, *convergence* was frequently observed when the preferred trajectory of an aircraft through the sector was uncertain as a result of adverse weather conditions such as thunderstorms. For example, in order to identify the location and magnitude of the adverse weather conditions, controllers gained an understanding of the usable airspace in their sector, by converging information from auxiliary screens with weather information, weather visualization on the radar display, aircraft deviations and requests for deviations, and information obtained from pilots. Controllers then used the obtained information in order to establish an understanding concerning the usability of routings and flight levels. Convergence allowed controllers to detect inconsistencies

Table 2 Action requirements and example sources of uncertainty

Categories of uncertainty	Action requirement (issue)	Example source	Type of uncertainty
System information uncertainty (status and integrity of the operational system)	Aircraft trajectory	System failures, resulting in missing flight plan details (estimates)	Lack of (reliable) information
	Pilot or controller's (shared) awareness about a clearance.	Verbal exchanges between controllers and pilots	
	Aircraft position	Radar failure (loss of signal of primary or secondary radar)	
	Aircraft altitude	Transponder failure	
	Availability of civilian airspace	Turbulence, thunderstorms	
	Availability of military airspace	Conflicted information provided by the system	
	Capacity of neighbouring sectors	System limitations, e.g. limits of radar coverage	
Procedural uncertainty	Procedural course of action and response strategy	Unanticipated deviation of procedures by others	Inadequate understanding and undifferentiated alternatives
		Applicable procedure unknown	
Traffic situation uncertainty	Traffic conflict (anticipated minimum separation and time until minimum separation is reached) and optimal traffic solution	Aircraft performance variability as a result of aircraft characteristics, engine parameter settings, and preferred flight profiles	Lack of (reliable) information and undifferentiated alternatives
		Aircraft performance variability as a result of winds	
		Adverse weather (e.g. thunderstorms)	
	Aircraft adherence to negotiated entry and exit agreements and optimal traffic solution	Aircraft performance variability as a result of aircraft characteristics, engine parameter settings, and preferred flight profiles	Lack of (reliable) information and undifferentiated alternatives
		Aircraft performance variability as a result of winds	
		Adverse weather (e.g. thunderstorms)	
Trajectory uncertainty	Aircraft intentions (preferred future trajectory) and response strategy	Military aircraft in military airspace	Inadequate understanding and undifferentiated alternatives
		Unknown intentions of neighbouring sectors	
		Aircraft (IFR, VFR) that are not in contact	
		Turbulence, thunderstorms	
		Special flight or emergency flight	
	Non-conformance of aircraft (deviations of trajectory) and intervention strategy	Adverse weather (e.g. turbulence, thunderstorms, winds)	Inadequate understanding and undifferentiated alternatives
		Pilot or controller error as a result of verbal exchanges between controllers and pilots (e.g. undetected incorrect read back)	
		Pilot of controller error (e.g. incorrect system entry)	

in the data in order to question the established mental picture about the location of the weather and the most optimal traffic solution.

4.2.2 Acknowledging uncertainty

The *acknowledgement* strategies and underlying tactics are described and summarized in Table 4.

4.2.2.1 Weighing pros and cons Uncertainty particularly influenced a controller's traffic plans when it was related to the traffic situation (e.g. a possible loss of separation between two or more aircraft, or the (in)ability of an aircraft to make it's agreed exit conditions). In such cases, controllers would *weigh pros and cons* by deciding: (1) whether or not to intervene; (2) when to intervene, whether to implement the solution in a strategic or in a tactical timeframe, and (3) what traffic solution to implement

Table 3 Uncertainty coping strategies: reducing uncertainty

Coping strategy	References	Tactic within strategy	Description of tactic
Reduction of uncertainty	Lipshitz and Strauss (1997)	Collecting information	Controllers collect information by consulting information systems, calling neighbouring (military) sectors, or contacting aircraft on the frequency
		Relying on informal rules of conduct	Controllers shift to using informal rules of conduct by doing what is safe, and what makes sense
Anticipatory thinking	Klein et al. (2007)	Pattern recognition	Controllers engage in selective attention and identify need for intervention by detecting deviations from expected patterns, based on stored patterns (knowledge), using cues in the operational environment
		Trajectory tracking (including mental simulation)	Controllers extrapolate the future traffic situation using *mental simulation* supported by controller support tools and *assumption-based reasoning*
		Convergence	Controllers combines information from various sources in order to create an understanding of the availability of routes and flight levels in the sector

within the strategic or tactical timeframe. Traffic solutions in a strategic timeframe (involving aircraft not yet in the sector) often included proposals for clearances to the previous sector, including flight level or routing in coordination with the subsequent sectors. Traffic solutions in a tactical timeframe (involving aircraft already in the sector), proposed by the radar planner, often concerned fine-tuned solutions, such as (phased) flight level instructions, or changes in heading or speed, which were then communicated to the radar executive, in order to be implemented in the tactical timeframe. Similarly, the radar executive would also weigh pro's and cons when choosing between traffic solutions within the tactical timeframe, for example by instructing aircraft to change flight level, heading or speed, or rate of climb/descent. Controllers decided between solutions by making trade-offs between the various operational goals. The importance of trade-offs when weighing pro's and cons between traffic solutions, either between the strategic and tactical timeframe, or within the same timeframe, is presented in Sect. 4.3.

4.2.2.2 Adaptable plans In our study, we observed that controllers often *adapted existing traffic plans* in response to uncertainty. These traffic plan adaptations were

Table 4 Uncertainty coping strategies: acknowledging uncertainty

Coping strategy	References	Tactic within strategy	Description of tactic
Weighing pros and cons	Lipshitz and Strauss (1997)	Weighing strategic versus tactical traffic solutions	The radar planner decides between implementing a strategic traffic solution or tactical traffic solution, to be implemented by the radar executive in the tactical timeframe
		Weighing traffic solutions within strategic or tactical timeframe	The radar planner or radar executive chooses between different traffic solutions within the strategic and/or tactical timeframe
Adaptable plans	Kontogiannis (2010), Hollnagel and Woods (2005)	Adaptive planning	Controllers dynamically decide on the usability of the airspace and adapt plans using alternative routing and location of holdings depending on operational conditions (e.g. the location of the adverse thunderstorms)
Forestalling (improving readiness)	Lipshitz and Strauss (1997)	Contingency or backup plan	Controllers develop specific backup plans in case the original plan fails. Backup plans may be shared implicitly or explicitly within the team as well as between sector teams
	Kontogiannis (2010), Hollnagel and Woods (2005)	Creating buffer zones in traffic flows (plan coupling)	Controllers maintain extra spacing between aircraft within traffic flows in order to accommodate possible future deviations from aircraft performance due to winds
	Kontogiannis (2010), Hollnagel and Woods (2005)	Increasing safety margins (plan coupling)	Controllers increase the safety margins (or minimum separation distance) between two aircraft as a precaution in case they are unsure about the behaviour of an aircraft
		Maximizing operational control	Controllers prefer to maximize operational control by being in contact with an aircraft in case a traffic situation may result in a potential loss of separation

primarily a response to cope with uncertainty, rather than a direct response to traffic complexity (e.g. traffic conflicts) or traffic flow efficiency. Adaptable strategic traffic plans provided controllers with the flexibility to deal with unpredictable sources of uncertainty that could have impacted the traffic flows. For example, the radar executive, under conditions of uncertainty, sometimes preferred a phased implementation of an aircraft's trajectory through the sector, in order to generate flexibility in terms of options. Adaptable planning was particularly observed in the case of adverse weather conditions such as thunderstorms. For example, the radar planner, in coordination with the approach sector, dynamically adjusted the location of holding circles and arrival flows depending on the location of the adverse weather (e.g. thunderstorms).

4.2.2.3 Forestalling Controllers also engaged in forestalling in order to prepare for possible adverse outcomes of uncertainty by (1) creating contingency or backup plans, (2) creating buffer zones in traffic flows, (3) increasing safety margins, and (4) maximizing operational control.

4.2.2.4 Contingency or backup plans We observed that controllers, when faced with high levels of uncertainty, explicitly shared contingency or backup plans. In particular, backup plans were explicitly shared within the sector team when the likelihood of implementing the backup plan was high. When a backup plan involved other sector teams, the radar planner would proactively share or coordinate this plan with other sectors, which then included information about the task distribution between the sectors. For example, a controller communicated to a neighbouring sector the following backup plan: "That flight level is ok, if he doesn't make it send it on a heading and I will advise Military". It should be noted that even if backup plans were not explicitly shared, it does not mean that they did not exist. As more than one controller stated: "There is always a backup plan".

4.2.2.5 Creating buffers zones in traffic flows (plan coupling) In certain cases, controllers preferred to *create buffer zones in traffic flows*, a strategy aimed at decoupling or reducing interdependencies of traffic plans, when aligning traffic for approach, such as when increasing the separation between aircraft within traffic flows. Controllers applied this tactic particularly when aircraft performance was difficult to predict, for example, in case of strong winds. The additional buffer zones between aircraft within flows allowed the controllers to maintain their original traffic plans and normal operations while being able to maintain safe separation between aircraft, as well as to accept any major changes in operational setting as a result of environmental conditions, for example, a change in runway operations.

4.2.2.6 Increasing tactical safety margins (plan coupling) An alternative way for controllers to create buffers by reducing interdependencies via decoupling was to increase tactical safety margins beyond the minimum separation distance. Controllers seemed to prefer this tactic when the behaviour of a particular aircraft could not be fully anticipated, such as if its trajectory through the sector was unknown or possible deviations from an intended trajectory could not be predicted. For example, a controller mentioned that in case there was a crossing involving an aircraft flying under visual flight rules ("VFR flights"), controllers would increase the separation (beyond the minimum separation) between an aircraft and a VFR flight, to "be on the safe side", when getting into contact with VFR flight would be too costly with respect to time and coordination requirements.

4.2.2.7 Maximizing operational control Controllers preferred to maximize operational control by requesting an aircraft on their frequency, by keeping an aircraft on their frequency, or by deliberately delaying handoff at the sector boundary. Controllers used this tactic when there was uncertainty about the intentions or behaviour of another aircraft that was not under their control. For example, during one of the observation sessions, there was uncertainty concerning the trajectory of an aircraft, which could possibly have generated a future traffic conflict. Although the traffic situation had already been resolved with the neighbouring centre, the actual implementation of the traffic solution was, for reasons unknown to the controllers, delayed by the neighbouring centre. The controllers responded to this situation by not handing off their aircraft to the subsequent sector at the sector boundary in order to remain in control of the situation. The controllers stated afterwards: "We preferred to keep our aircraft on our frequency until we were sure that separation could be assured, as we were just not sure what he [the aircraft under control of the neighboring center] was going to do".

4.2.3 Increasing uncertainty

The strategies related to *increasing* uncertainty and underlying tactics are described and summarized in Table 5.

4.2.3.1 Increasing uncertainty through creating flexibility In addition to strategies aiming to reduce or acknowledge uncertainty, we also identified a new strategy:

Table 5 Uncertainty coping strategies: increasing uncertainty

Coping strategy	References	Tactic within strategy	Description of tactic
Increasing uncertainty by increasing operational degrees of freedom through delegation of control within specific boundaries	Grote (2015)	Aircraft release	Controllers delegate the control of an aircraft to the next subsequent sector (under certain restrictions), by sending the aircraft to the frequency of the subsequent sector before it has reached the boundary of their sector (i.e. area of responsibility)
		Pilot discretion	Controllers may give pilots operational degrees of freedom by granting pilots the opportunity to execute the instruction at their discretion (i.e. leaving the timing of the execution and climb/descent rate up to the pilot)
		Clearing aircraft on a heading	Controllers give pilots operational degrees of freedom aircraft to fly on a heading to avoid thunderstorms and to intercept their original trajectory again when possible

flexibility through delegation of control within specific boundaries. On some occasions, controllers preferred to increase uncertainty as a means of increasing the flexibility of operations for neighbouring sectors or pilots, in order to obtain their goals and objectives. In such cases, controllers *defined specific boundaries or conditions* within which they accepted uncertainty. The three tactics we identified as part of this strategy are *aircraft release* and *pilot discretion* and *clearing aircraft on a heading.*

4.2.3.2 Releasing an aircraft A tactic within this strategy refers to the delegation of control by *releasing* an aircraft to the next sector well *before* the aircraft reaches the sector boundary, by sending the aircraft to the frequency of the subsequent sector. This means that the aircraft, while still in the previous sector, is under control of the next sector. In most cases, restrictions apply to the release, for example, by releasing an aircraft for descent or turn only. A release allows the subsequent sector to initiate descent/ascent or turn before the aircraft reaches the sector boundary, allowing more manoeuvring space and time for conflict resolution or traffic optimization, and thus extra operational degrees of freedom to obtain their operational goals. However, a release *increases* uncertainty for controllers in the current sector, as the aircraft in their sector is not under their direct command and the trajectory of the aircraft will be dependent on the plans of the subsequent sector. A sector will therefore only release an aircraft under conditions in order to ensure that it does not generate traffic conflicts. The delegation of authority and control regarding the command of the aircraft did not change the responsibility distribution between controllers: the delegating sector remained responsible for the released aircraft, which was enabled by the controller's ability to regain control quickly by having the aircraft transferred back on the frequency in order to resume authority, at any time.

4.2.3.3 Pilot discretion We observed that controllers increased the operational degrees of freedom for pilots by granting them the opportunity to execute the instruction at their discretion, leaving the decision latitude to the pilot concerning the *timing* of the implementation as well as the *speed* and *rate of climb/descent*. With pilot discretion, controllers leave the *timing* of the implementation up to the pilot, as long as the aircraft reaches its flight level at the waypoint as instructed. This created flexibility for the pilot to adhere to their operational goals (e.g. avoiding weather or increasing comfort in case of turbulence).

4.2.3.4 Clearing an aircraft on a heading Under some conditions, controllers increased operational degrees of freedom for pilots by allowing them to fly on a heading. The longer the aircraft flies on a heading, the higher the level of uncertainty. In contrary to other clearances, clearing an aircraft on a heading does not close the coordination loop, as the aircraft is not cleared to a specific waypoint, which generates high variability with respect to the actual trajectory flown until the pilot resumes the initially planned trajectory. This strategy increased uncertainty for controllers significantly, as it generated reduced predictability related to the aircraft's future position, its trajectory through the sector, as well as reduced predictability regarding potential conflicts with other aircraft. This tactic was particularly used when pilots needed to deviate from the trajectory to avoid thunderstorms.

4.3 Contingencies relevant for choosing uncertainty management strategies

In this section, we describe three contingencies that influenced the adoption of uncertainty management strategies: (1) the timeframe of operations, (2) trade-offs between operational goals, and (3) operational constraints.

4.3.1 Strategic versus tactical phase

We identified that controllers used different complexity and uncertainty management strategies, depending on the timeframe (Table 6). Furthermore, we also found that complexity and uncertainty management strategies executed in the strategic phase also had an impact on the level of complexity and/or uncertainty in the tactical phase. The following strategies were identified:

- Strategies directed to *reduce* complexity in the strategic or tactical phase (e.g. by implementing traffic solutions), which may also *indirectly acknowledge* uncertainty in the tactical and strategic phase;
- Strategies directed to *acknowledge* complexity in the strategic or tactical phase (e.g. by moderating/buffering the cognitive demands or workload required to managing complexity);
- Strategies directed to *reduce* or *acknowledge* uncertainty in the strategic or tactical phase, which may also *indirectly reduce the complexity* of the traffic (e.g. adaptable traffic plans, increase of safety margins);
- Strategies directed to *increase* uncertainty in the tactical timeframe for the purposes of increasing operational flexibility (e.g. release of an aircraft to the next sector before the sector boundary).

4.3.2 Trade-offs between operational goals

The results showed that controller's priorities between different operational goals, and the trade-offs between operational goals, further influenced the adoption of complexity and uncertainty management strategies. We identified four operational goals:

Risk/safety	Associated risks, including safety, related to the solutions in the strategic or tactical timeframe
Efficiency/service	The efficiency of the solution (fuel burn, miles flown) and the preferred level of service
(Future) Workload/capacity	The (future) workload required for the implementation of the traffic solution in relation to available capacity
Flexibility/stability	The required level of flexibility versus stability for other actors in the system

We observed that these operational goals had a strong influence on whether controllers preferred to implement a strategic or tactical solution. Controllers preferred tactical solutions to strategic solutions when:

- There were sufficient viable options or simple solutions within the tactical timeframe (*risk/safety*);
- The most optimal solution would be more apparent in the tactical timeframe, when a traffic conflict would resolve itself in the tactical timeframe, or when the radar planner was uncertain about the preference of the radar executive or the pilot (*efficiency*);
- The radar executive would have sufficient capacity to deal with the tactical conflict (*workload/capacity*);
- Flexibility (e.g. possibility to adapt a plan in tactical timeframe) was preferred over stability/predictability (*flexibility* vs. *stability*);

The trade-off of *flexibility* versus *stability* seemed to be particularly relevant when deciding between a strategic versus a tactical solution when managing uncertainty. Strategic solutions generate stability (by increasing the predictability of the trajectory); however, implementing a strategic solution (e.g. expediting traffic through direct routings) could also cause disruption of the arrival sequence, thereby reducing the efficiency of operations. Thus, in this situation, *stability* is a trade-off with *efficiency*. Similarly, tactical solutions generate flexibility due to the possibility of adapting the traffic plan in the tactical timeframe. However, tactical traffic plans generate higher levels of *workload* for the radar executive in the tactical phase. Thus, in this situation, *flexibility* is a trade-off with *workload*.

The four operational goals also functioned as trade-offs when choosing strategies *within* the strategic or tactical timeframe. For example, in the case of a release, the benefits in terms of increased operational freedom (*flexibility*) would be traded off when the costs related to the release (e.g. possible *risk/safety* impacts) and the workload related to coordinating such a release (*workload/capacity*) would be too high.

4.3.3 Operational constraints

Additionally, we focused on the *operational constraints* that could influence the adoption of uncertainty coping strategies. The results indicate three relevant contingency factors: predictability of uncertainty, urgency of response, and available resources.

The first operational constraint that influenced the adoption of strategies was the *predictability* of the source of uncertainty. For example, thunderstorms are relatively predictable for controllers, whereas turbulence is not, thus requiring different strategies. Adaptable planning was particularly successful in case of thunderstorms, as the location and future development of thunderstorms could be anticipated, whereas turbulence generally required higher levels of convergence before adaptable plans could be developed. The second operational constraint identified involved time pressure, that is, the *urgency of the*

Table 6 Complexity and uncertainty management strategies

Strategy	Timeframe	Tactics within strategy
Complexity management		
Reducing complexity which may indirectly acknowledge uncertainty	Strategic timeframe	*Strategic traffic plans*
		Acknowledge complexity by solving possible traffic conflicts in a strategic timeframe:
		Coordinate new flight level outside sector
		Coordinate different exit conditions (exit flight level or exit waypoint)
		Coordinate direct routing
	Tactical timeframe	*Tactical traffic plans*
		Acknowledge complexity by solving possible traffic conflicts in a tactical timeframe:
		Separate aircraft vertically (minimum of 1000ft separation)
		Separate aircraft horizontally (minimum of 5 nm), then descent through each other's level
		Separate aircraft using heading, speed, or send aircraft on diverging tracks
Acknowledging complexity	Strategic and tactical timeframe	*Use of mental abstractions*
		Grouping traffic into traffic flows, conflict pairs, aircraft on the same flight level
		Identification of critical points (waypoints, conflict points)
		Assignment of aircraft into "in conflict" or "not in conflict"
		Optimization of work process
		Leaving measuring and planning tools active to support monitoring functions
		Suppressing irrelevant information
		Optimizing layout (location of windows, avoid cluttering of information on radar display, such as aircraft label information)
		Workload management
		Reducing workload for repetitive functions to free up cognitive capacity for complexity
Uncertainty management		
Reducing uncertainty	Strategic and tactical timeframe	*Reducing*
		Searching for additional information
		(In)formal rules of conduct
		Anticipatory thinking
		Assumption-based reasoning
Acknowledging uncertainty which may indirectly reduce complexity	Strategic and tactical timeframe	*Weighing pros and cons*
		Weighing pros and cons when choosing between traffic solutions:
		Weighing strategic versus tactical traffic solutions using trade-offs
		Weighing options within strategic or tactical timeframe using trade-offs
		Adaptive planning
		Forestalling
		Creating buffer zones in traffic flows (plan coupling)
		Increasing safety margins
		Contingency or backup plans (plan coupling)
	Tactical timeframe	*Forestalling*
		Maximize operational control
Increasing uncertainty	Strategic and tactical timeframe	*Increasing operational degrees of freedom through delegation of control within specific boundaries*
		Aircraft release
	Tactical timeframe	*Increasing operational degrees of freedom through delegation of control within specific boundaries*
		Pilot discretion
		Clearing aircraft on a heading

response. Time pressure limited the possibilities for controllers to engage in uncertainty coping strategies that were more time-consuming, shifting the preference towards adopting strategies that facilitated a quick response to the situation. For example, in the case of procedural uncertainty, controllers preferred to rely on informal rules of conduct by doing "what is safe", rather than trying to ensure that the correct procedure was followed (the *urgency* is high). The third operational constraint was the *availability of capacity and resources*. For example, controllers only released an aircraft when the required airspace for the release was available (e.g. no interfering traffic), that is, when they had sufficient resources in terms of airspace and time for intervention to release an aircraft safely.

4.4 Automation support for uncertainty management

Additionally, we focused on how automation supported controllers with managing uncertainty. The results showed that the automated system, including controller support tools and various HMI functions, supported controllers in reducing, acknowledging, and increasing uncertainty. An overview of automation requirements supporting complexity management and uncertainty management strategies is provided in Table 7.

First, the system supported controllers in *reducing* uncertainty by providing reliable, real-time information about the traffic, as well as the reliability and integrity of the overall system. The system also supported the reduction of uncertainty, by supporting the awareness concerning the intentions and actions of a controller's team member, through the "closing the loop" function. This function displayed all executed clearances on both displays by highlighting the clearance in the aircraft label until it was "clicked" by the other controller as confirmation of their awareness. The system also supported *anticipatory thinking*, by supporting controllers with *detecting patterns*, by facilitating the detection of abnormalities or deviations such as traffic conflicts (through conflict detection tools) and deviations from the cleared trajectory (through monitoring tools). The system also supported controllers with *trajectory tracking*, by supporting the *mental simulation* of the future trajectory through planning tools and extrapolated speed vectors. Second, the system supported controllers also in *acknowledging* uncertainty, by enabling the development and implementation of adaptable traffic plans that ensure high levels of flexibility through the dynamic use of airspace. For example, controllers were able to dedicate any waypoint as holding waypoint when the standard holding waypoints would not be available due to thunderstorms. Third, the system supported controllers by *increasing* uncertainty through enabling delegation of control (e.g. release), in order to increase the flexibility of other actors in the system, while respecting a balance between autonomy and control. For example, the delegating controller was able to set restrictions to the sector requesting the release, as well as have the availability to regain control quickly if needed.

We were also interested in how automation in air traffic control dealt with the existing challenges of automation incorporating uncertainty into conflict prediction tools. Our findings revealed that the conflict detection tools did not integrate uncertainty originating from factors such as winds, into conflict prediction algorithms. Instead, conflict prediction was based on *human algorithms*. Traffic conflict analysis therefore mainly relies on manual trajectory tracking through mental simulation as well as experience when integrating the impact of environmental conditions. Finally, it was observed that the visualization of uncertainty in terms of degrees of probabilities was not preferred, as this would increase display clutter. An exception was the presentation of the weather radar, as overlay on the traffic picture, which could be activated by the controller when needed.

5 Discussion

In this section the results are discussed in context of existing literature and summarized in the air traffic controller complexity and uncertainty management model.

5.1 Action requirements and sources of uncertainty

This study was the first study to provide a detailed overview of the sources of uncertainty, grouped by the action requirements that they generated for controllers in air traffic control. In line with Lipshitz and Strauss (1997), we separated uncertainties in terms of their issue (which we referred to as action requirement), their source, and the type of uncertainty and showed that all *types* of uncertainty (c.f. Lipshitz and Strauss 1997) could be identified. We believe that the presented overview (see Table 1) is useful for future research in air traffic control, as to date, action requirements, sources, and types of uncertainty have often been used interchangeably to refer to uncertainty in air traffic control operations. This overview may facilitate the understanding of uncertainty, which, in turn, may support discussions on uncertainty in current as well as future air traffic management operations as envisioned within SESAR and NextGen.

Table 7 Automation support for uncertainty management strategies

Uncertainty management strategy	Examples of automation supporting uncertainty management strategies
Collecting information	*Display of reliable and accurate information where needed*
	The system provides *real-time* and accurate data
	The system allows a *shared understanding* regarding the clearances through the "closed the loop" function of the Electronic coordination tool
	The system allows insight into relevant *sector characteristics* on demand through the visualization of sector characteristics (e.g. routings, country boundaries, waypoints)
	The system supports visualization of *limitations and constraints* of neighbouring sectors, including the availability of airspace, current capacity/workload of neighbouring sectors (keyboard shortcuts that show traffic above or below own sector)
Anticipatory thinking	*Pattern recognition*
	The system supports *timely detection of missing, conflicting or unreliable information* through (visual) system notifications (highlighted text) or alerts (e.g. in case of radar failure)
	The system allows the visualization of routings and waypoints on the radar map, supporting the detection of abnormalities and deviations from routings by aircraft from these routings and waypoints
	The system supports detection of traffic flows and the comparison to expected/stored patterns (e.g. history dots in aircraft tracks, speed vectors, and arrow symbols in aircraft label to indicate vertical evolution)
	The system supports visualization of traffic on each flight level in the sector ("Click and hold" tool) and traffic to the same exit points (ECAT window)
	Conflict detection tools (HST, ECAT and DST) support the detection of traffic in conflict versus not in conflict, by highlighting traffic conflicts
	Monitoring tools (CLAM and RAM function) support the timely identification of aircraft deviations (lateral or vertical) by highlighted text in the flight label
	Trajectory tracking
	Aircraft labels reduce *fixating* by supporting controllers with tracking aircraft progress by presenting continuous data about aircraft behaviour and performance
	Speed vectors and extrapolated speed vectors support *mental simulation* of the future trajectory
	Conflict detection tools (HST, ECAT and DST) support *vigilance* by following human algorithms, supporting controllers in critiquing and validating conflict predictions
	Conflict detection tools (HST and DST) supports mental simulation of anticipated conflicts by *extrapolating trajectories of conflicting aircraft, visualizing* the *conflict configuration*, and *presenting* real-time information about time until minimum separation and minimum distance
	Measuring tools support detection of possible discrepancies between planned and actual state (e.g. by supporting the assessment of separation distance between aircraft at a future crossing point)
	Convergence
	The HMI supports convergence of data, for example, through optional visualization of weather (weather radar image) on top of the traffic picture
Weighing pros and cons	*Weighing pros and cons*
	The HMI supports the visualization of sector characteristics of neighbouring sectors (traffic situation, traffic complexity, availability of flight levels)
	The HMI supports insight into operational goals of other sectors and pilots (e.g. workload of other sectors, aircraft delays)
Adaptive plans	*Developing adaptive plans*
	Planning tools support the simulation and probing of possible alternative trajectories (e.g. headings)
	E-coordination allows exchange of strategic and tactical traffic solutions (proposals and requests) independently between sectors
	Overall system and procedures support the implementation of adaptive plans (e.g. ability to change flight plans, routings and location of holding patterns)
Forestalling	*Maximizing operational control*
	Procedures allows controllers to remain in control if deemed necessary, for example, by keeping aircraft on frequency
Delegation of control within specific boundaries	*Delegation of control within specific boundaries*
	System allows delegation of control to other sectors, supported with clear delegation procedures (aircraft release) and balance between autonomy/control mechanisms

5.2 Strategies for managing uncertainty

Our results confirm that the uncertainty-reduction strategies as described by the RAWFS heuristic (Lipshitz and Strauss 1997) and *anticipatory thinking* (Klein et al. 2007), can be identified as air traffic controller strategies in enroute air traffic control. Anticipatory thinking has long been recognized in air traffic control as an important strategy during perception and decision-making tasks. For example, various previous studies have argued that separation assessment heavily relies on visual mental cues and the processing of patterns (e.g. Averty et al. 2008; Nunes and Mogford 2003; Xu and Rantanen 2003), supported by mental abstractions to reduce traffic complexity, by grouping traffic into traffic flows, groups of interacting aircraft, critical points (e.g. Histon et al. 2002), and assignment of aircraft into "in conflict" or "not in conflict" (e.g. Kirwan and Flynn 2002; Niessen and Eyferth 2001; Rantanen and Nunes 2005). Similarly, earlier work has stressed the importance of mental extrapolation for conflict detection and separation (Averty et al. 2008; Boag et al. 2006; Xu and Rantanen 2003). Finally, our findings partially replicate earlier findings of Malakis and Kontogiannis (2013) and Malakis and Kontogiannis (2014), who illustrated how air traffic controllers reduce uncertainty through sensemaking, which aims at understanding and anticipating situations in uncertain situations. This finding is not surprising, as anticipatory thinking reflects different types of strategies that support sensemaking (Malakis and Kontogiannis 2014; Klein et al. 2006b).

Less was known about the strategies that controllers adopt to acknowledge uncertainty. Our findings have illustrated that controllers use a wide variety of uncertainty acknowledgement strategies, including adaptive planning (c.f. Kontogiannis 2010; Hollnagel and Woods 2005). Although adaptable planning has been acknowledged as an important adaptive strategy in response to uncertainty (Kontogiannis 2010), previous studies have not presented specific examples for air traffic control. In contrast, replanning, which refers to the implementation of new plans after an original plan has failed (Kontogiannis 2010), was rarely observed in our study. A possible explanation for this is that replanning in a tactical timeframe may increase time pressure and decreased options in the tactical timeframe (e.g. Kontogiannis 2010), negatively impacting operational goals by increasing workload and reducing the flexibility to manage traffic situations, in particular when operational constraints are already unfavourable. This may explain why, in our study, controllers preferred to develop adaptable plans, which could provide alternative options while a plan was being executed, without requiring replanning. Furthermore, we also identified that loose-coupled plans (c.f. Kontogiannis 2010; Hollnagel and Woods 2005) are an important strategy to manage uncertainty. However, this strategy has up to now mainly been discussed in context of error detection (Kontogiannis and Malakis 2009) and has not previously been identified as an uncertainty coping mechanism. Finally, we could identify the uncertainty acknowledgement strategies, as identified by Lipshitz and Strauss (1997), including weighing pros and cons and forestalling. One tactic, maximizing operational control, can be considered as a new tactic of forestalling.

In addition to uncertainty-reduction and acknowledgement strategies, our study provides support for recent arguments by Grote (2015), who stated that decision-makers under specific conditions may sometimes prefer to *increase* uncertainty, rather than to reduce or to acknowledge it. Our study identified a new strategy (increasing operational degrees of freedom through delegation of control) with three underlying tactics (*aircraft release*, *pilot discretion,* and *clearing on a heading)* belonging to this strategy. Increasing uncertainty has, to date, not been identified as a coping strategy in air traffic control. Delegation of control within specific boundaries is an example of task delegation, which refers to situations where an actor gives the authority to another actor to perform a task (Straussberger et al. 2008).

5.3 Contingencies relevant for choosing uncertainty management strategies

Within the context of traffic complexity, the trade-off factors long considered the most important are risk/safety, efficiency, and workload (e.g. Hilburn 2004; Kirwan and Flynn 2002; Loft et al. 2007; Malakis et al. 2010). In particular, these trade-offs have been discussed in the context of explaining how controllers choose between strategic and tactical traffic solutions (e.g. Athenes et al. 2002; Kontogiannis and Malakis 2013; Loft et al. 2007). Athenes et al. (2002) refer to this trade-off as the *late/accurate/costly* versus *early/imprecise/economical* control actions. Our study contributed to these earlier findings by placing these trade-offs within the context of uncertainty, by suggesting that these trade-offs similarly apply for uncertainty coping strategies as well as complexity coping strategies. Finally, in addition to these three trade-off factors, we identified a fourth trade-off, loss/gain of flexibility/stability, which can be traded for or against other outcomes (risk/safety, efficiency, workload).

Our research identified three sources of operational constraints that influence the adoption of uncertainty coping strategies: the *predictability of uncertainty*, the *urgency of the response,* and the *availability of resources*. Lipshitz and Strauss (1997) similarly argued that decision-makers tend to use acknowledgement strategies when reduction strategies are either too costly or not feasible. However, our results indicate that these contingencies do not only influence a shift from reduction to acknowledgement strategies, but also influence the choice between different types of reduction and acknowledgement strategies. In addition, the results indicated that controllers initiated various uncertainty management strategies in parallel, enabled by dynamic task distribution within the team. This suggests that the management of uncertainty through dynamic task distribution requires that controllers have a sufficient and shared understanding the demands and corresponding responses as well as each other's mutual capacity to engage in such responses.

5.4 Summary

The air traffic controller complexity and uncertainty management model, based on the findings presented in the previous sections, is illustrated in Fig. 9.

As illustrated in the model, controllers adopt complexity and uncertainty management strategies depending on the *trade-offs* of operational goals (*Risk/Safety*, *Efficiency*, *Workload* and *Flexibility* vs. *Stability*), supported by automation and within the context of *contingencies* occurring in the operational environment. Furthermore, the level of complexity and uncertainty occurring in the strategic and tactical phase are differentiated as separate operational states. Complexity impacting operations in the tactical phase originates from the complexity that is (deliberately) not resolved in a strategic timeframe and the complexity that originates from (un)expected disturbances in the tactical timeframe. Similarly, uncertainty impacting operations in the tactical phase is the uncertainty that is occurring in the tactical phase as well as any *residual* uncertainty impacting tactical operations that was not or could not be managed in the strategic phase. Finally, the model acknowledges that complexity and uncertainty do not occur independently in operations. Complexity management strategies executed in the strategic phase may have impact on the level of complexity as well as uncertainty in the tactical phase, and vice versa, as the level complexity and uncertainty can be affected by a single strategy or intervention at the same time.

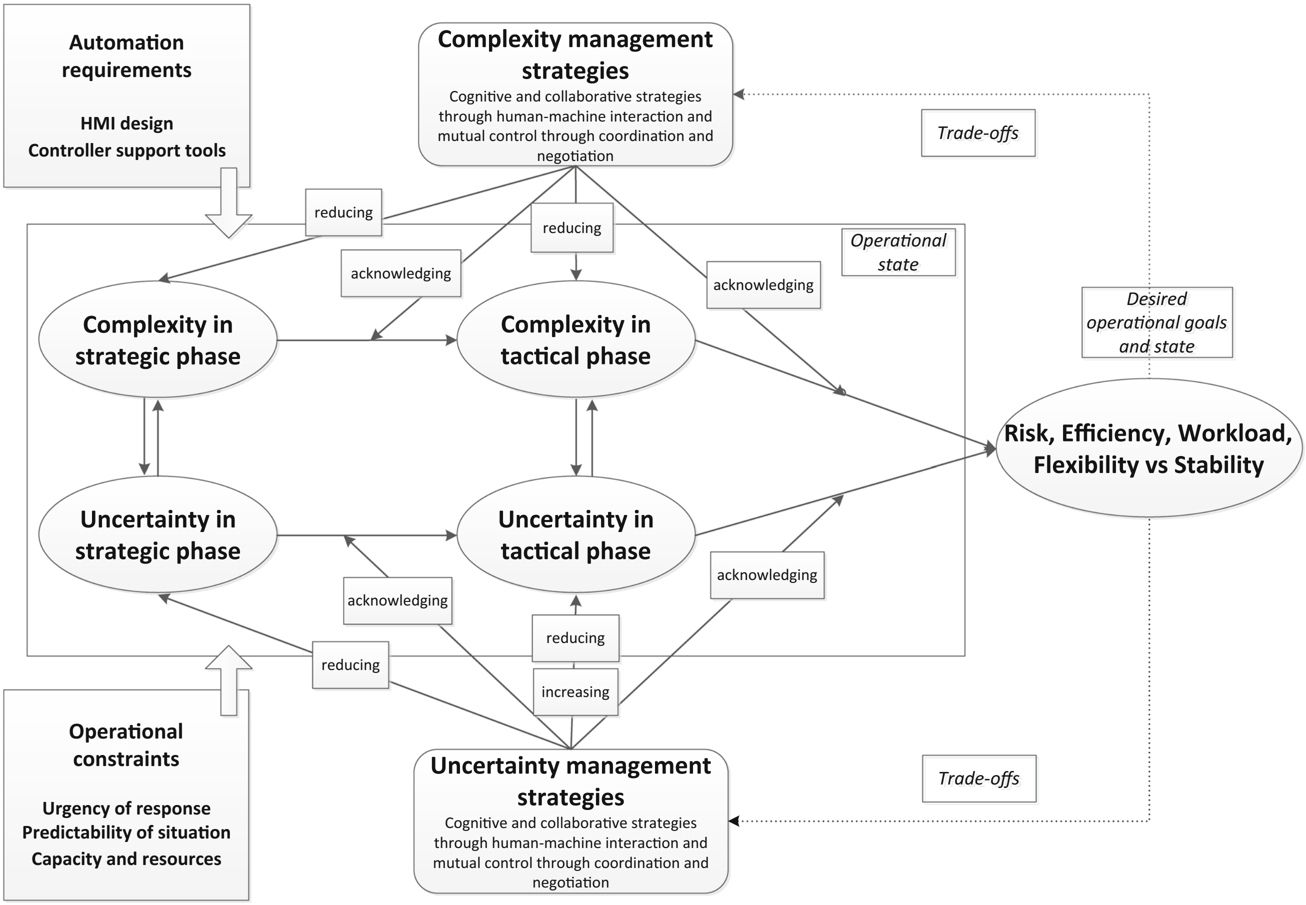


Fig. 9 Air traffic controller complexity and uncertainty management model

6 Implications

In this section, we discuss the implications of our study as well as the limitation of study in two different sections (a) implications for training and (b) implications for automation design, for current operations as well as future concepts of ATC operations.

6.1 Implications for training

The findings have important implications for ATC training. A better understanding of uncertainties in enroute air traffic control and the management of these uncertainties may particularly benefit trainings for novice controllers, during initial training, as well as for licensed controllers, during Team Resource Management (TRM) trainings. Explicit focus on the management of uncertainty in these trainings, for example, by discussing effective responses in context of operational constraints and goals, may improve a team's mental model regarding effective strategies in the context of these operational constraints and goals, which, in turn, may even further support the efficiency of operations through the reduction of explicit coordination.

6.2 Implications for automation design

The results showed that current ATC automation is designed to optimally support uncertainty management strategies through controller support tools, HMI functionality, as well as overall system design. We will now discuss the implications for automation design in the context of current operations, as well as future operations as envisioned within SESAR and NextGen.

6.2.1 Implications for current operations

The results indicated that various controller support tools and functions (e.g. monitoring tools, alerts in case of radar failure, see Table 7) support controllers with reducing uncertainty. The findings indicated that the detection of uncertainty, with support of automation, is preferred if (1) the data behind these functions are reliable, (2) non-detection has a high impact on safety (e.g., deviation from routing or flight level), and (3) the cognitive demand on detecting such sources of uncertainty, as a result of monitoring, is high. Furthermore, the results showed that *uncertainty* (e.g., possible conflict or non-adherence to cleared route or flight level) was visualized by highlighting this information in a different colour code. Interestingly, other options for the presentation of uncertainty (mathematically, through probabilities or confidence limits, or visually, through shading or different levels of saturation) as proposed by Nicholls (2001) were not identified. An exception was weather radar information. A possible explanation is these visualization options may increase display clutter (c.f. Rosenholtz et al. 2005). Therefore, when designing systems that should alert controllers of missing, conflicting, or unreliable information, care must be taken to ensure appropriate design trade-offs between the visualization of uncertainty and possible risk of increasing display clutter. Furthermore, if visual or acoustic alerts are chosen to notify controllers of uncertainty, particular attention must also be directed at optimizing the *timing* and *sensitivity* of these alerts, in order to reduce *nuisance* alerts and to ensure *vigilance* and *trust in automation* (e.g. Parasuraman and Manzey 2010; Parasuraman and Wickens 2008). Finally, the design of these alerts must also take into account various design trade-offs: notifications in colour may sometimes be missed, whereas animated alerts may have disadvantages in terms of their intrusiveness and cognitive costs related to processing these alerts (Imbert et al. 2014).

The results also showed that conflict detection tools deliberately did not reduce uncertainty by integrating sources that may generate variability into the algorithms underlying the conflict detection tools. Instead, the algorithms underlying the predictions of these tools were based on human algorithms, in favour of integrating more sophisticated aircraft performance models, as these models currently still suffer from reliability (c.f. Knorr and Walter 2011). This may support controllers in various ways. First of all, it can reduce *fixating* and increase controller *vigilance* by stimulating manual trajectory tracking through mental simulation and experience, while preserving controllers' conflict detection and analysis skills (c.f. Leroux 1999). These conclusions are supported by the notion of *transparency* and the concept of *appropriate reliance* (Lee and Moray 1994; Lee and See 2004). Appropriate reliance states that the understanding of humans concerning the capabilities of automation should match the actual capability of the automation, allowing humans to decide when it is reliable and when it is not (Lee and Moray 1994; Lee and See 2004). Finally, the findings are in line with earlier arguments by Averty et al. (2008), who stated that reducing uncertainty to a maximum is not a primary concern for controllers, as they, instead, prefer to accept a certain degree of uncertainty. Our findings suggest that incorporating uncertainty into automation (and thus by aiming to reduce it) may not be preferred, when preferred levels of reliability cannot be achieved.

In addition, the results have indicated the importance of strategies that acknowledge uncertainty. System characteristics that enable flexibility through flexible rules and procedures are required for current and future operations in order to enable controllers to acknowledging uncertainty by creating adaptable traffic plans in order to maintain efficient traffic flows, even during extreme environmental conditions and other operational disturbances. Various controller support tools supported controllers with acknowledging uncertainty. Future operations would benefit from even more sophisticated controller support tools, such as "What-if" tools (e.g. FASTI 2006, 2008) which enable the "probing" of different traffic solutions against operational goals. Finally, the results have shown that strategies, such as delegating control, which increases uncertainty, is often preferred in order to maintain flexibility of operations. This suggests that systems and operating procedures are required that support the management of delegation scenarios, for example, through monitoring tools that are able to detect when a delegated situation may exceed the constraints of boundaries of control.

6.2.2 *Implications for future operations in SESAR and NextGen*

Future ATM concepts, as envisioned within SESAR (SESAR JU 2012) and NextGen (FAA 2014), aim to increase the efficiency and predictability of air traffic management through the implementation of 4D business trajectories. Although these programmes aim to minimize uncertainty, uncertainty cannot be completely eliminated from future operations (Malakis and Kontogiannis 2014; Nicholls 2001). In particular, during non-routine events (e.g. adverse weather or emergency situations), pilots may need to deviate from their previously negotiated 4D business trajectory, requiring negotiation with controllers to exchange and implement adapted trajectories through the sector. This means that controllers may be confronted with even higher levels of uncertainty, due to increased ambiguity concerning the pilot's ability to maintain its 4D trajectory and their preferences (Dekker and Woods 1999; Malakis and Kontogiannis 2014; Nicholls 2001). Similarly, as the 4D business trajectory concept relies on the Free Route Airspace concept, the predictability of the traffic situation may significantly decrease, as conflicts between aircraft may now occur randomly in the sector, instead on standard routings. Taken together, this means that the role of uncertainty may increase for future operations. This suggests that future automation should support controllers with reducing, acknowledging as well as increasing uncertainty, by developing automated systems that enable delegation of control and authority between actors in the system, as well as controllers support tools that support controllers with managing uncertainty. For example, this study revealed that controllers also prefer to *increase* uncertainty, as a strategy to enable increased flexibility of operations. This finding has important implications for system design for future operations envisioned within SESAR and NextGen, as it requires a dynamic allocation of authority, control, and responsibility (Boy and Grote 2009, 2011; Flemisch et al. 2012; Straussberger et al. 2008) between all operators (human and automation) involved in managing the 4D trajectory. The delegation of control, an example of dynamic function allocation, should be carefully considered within the system design, by ensuring that the delegated tasks are clearly defined, and that the involved actors have a shared understanding about the operational goals, the constraints, as well as the progress of the delegated tasks (Straussberger et al. 2008). If not, delegation of control can generate unacceptable levels of uncertainty, leading to increased collaboration demands (Kontogiannis 2010), which would generate workload as an unwanted trade-off.

7 Limitations of study and conclusion

We acknowledge some limitations of this study. First of all, data were collected exclusively in enroute air traffic control sectors, suggesting limitations for external validity to other environments. Some of the findings, in particularly the automation requirements, are specific to enroute air traffic control environments. However, the findings can be translated to other command and control environments, where complexity and uncertainty management strategies are required to manage operational demands. Furthermore, the limited hours of observation means that the list of strategies and underlying tactics may not be exhaustive. In addition, we did not observe emergency scenarios or other highly abnormal situations, which are typical scenarios for high levels of uncertainty (Malakis et al. 2010; Kontogiannis and Malakis 2013). Finally, our study did not investigate the influence of team cognition (e.g. team mental models, team situation awareness) on uncertainty management (e.g. a team's ability to anticipate and to respond to uncertainty) as an aspect of adaptive team performance (c.f. Burke et al. 2006). Future research could further explore the influence of a teams' externalized cue-strategy associations (c.f. Fiore et al. 2010) on a team's ability to manage uncertainty.

In conclusion, the purpose of this study was to identify the sources of uncertainty occurring in enroute air traffic control, and the strategies that controllers adopt to respond to these sources of uncertainty. Existing frameworks, including the RAWFS heuristic (Lipshitz and Strauss 1997) and anticipatory thinking (Klein et al. 2007), proved successful in identifying reduction and acknowledgement strategies, and a few new tactics were described. In addition, in line with Grote (2015), we identified that controllers also preferred to increase uncertainty, in order to increase the flexibility of operations, and described new underlying tactics. Furthermore, we showed that various trade-offs between operational goals and contingences influenced the adoption of uncertainty management strategies, and showed how automation including controller support tools and HMI functions supported controllers with managing uncertainty. Implications for the design of current, as well as future ATM operations, as envisioned within SESAR and NextGen, were discussed.

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Appendix: Overview of controller support tools (adapted from Corver and Aneziris 2014)

Stripless tools	Description of the tool
Electronic coordination	
E-coordination tool	The E-coordination tool (Fig. 2) allows controllers of different sectors to electronically coordinate changes to the trajectory of a flight, e.g. by proposing a rate of descent/ascent, a flight level, or a direct route
Medium-term conflict detection tools	
Horizontal scanning tool (HST)	The horizontal scanning tool (HST, Fig. 3) is a conflict detection function whose outcome is displayed on the radar display, in the aircraft label and in a separate window which lists potential conflicts (encounters) having a horizontal separation of 10 nautical mile or 15 nautical mile or less (encounter threshold)
Exit conditions assistance tool (ECAT)	The exit conditions assistance tool (ECAT, Fig. 4) supports controllers in planning aircraft through the sector in a timely manner by listing all aircraft planned to exit at an exit point, sorted according to their predicted exit times. Potential exit conflicts are identified by highlighting the exit flight levels of these flights. In addition, controllers are presented with a suggested solution. Exit conflicts arise if exit conditions (typically three or more minutes of separation between aircraft, or as specified in letters of agreement between centres) cannot be complied with
Dynamic scanning tool (DST)	The dynamic scanning tool (DST, Fig. 5) displays a prompt window when a controller enters a solution which, according to the system, is unsafe. This prompt window displays information about the potential crossings, including minimum distance and time until minimum distance is expected. The trajectories are marked in red where loss of separation is predicted
Analysis support tool	
Crossing tool	The crossing tool (Fig. 6) helps controllers in the analysis of a potential conflict situation and with the monitoring of a crossing situation. When using the crossing tool, the controller selects the two aircraft to be monitored against each other and the system extrapolates their positions to calculate the minimum separation between them
Click and hold	The click and hold tool (Fig. 7) allows controllers to analyse the traffic situation by selecting a flight level in a dropdown menu. Only traffic which is cleared to this flight level and/or descends/climbs trough this level is highlighted
Planning and measuring tools	
Planning tools	Planning tools include speed vectors for each aircraft, which can be extrapolated based on the present heading and speed, as a result of the interaction with the mouse wheel (extrapolation of the future position in increments of minutes), thus giving visual information about the future position of the aircraft

continued

Stripless tools	Description of the tool
Measuring tool	The measuring tool supports controllers in measuring distances between aircraft, between trajectories, or critical points)
Monitoring aids	
Cleared level adherence monitoring function (CLAM)	The cleared level adherence monitoring function (CLAM, Fig. 8) is a monitoring aid that monitors actual flight level of the aircraft against the cleared flight level (CFL) given to the pilot and entered by the controller in the system. It provides a warning in case of a deviation
Route adherence monitoring (RAM) function	The route adherence monitoring (RAM) function is a monitoring aid to support controllers in detecting that an aircraft has deviated from the trajectory as known to the system. An alert warns the controller if the current aircraft flight path deviates from the trajectory as expected by the system

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