Cogn Tech Work (2014) 16:211–227
DOI 10.1007/s10111-013-0258-7

ORIGINAL ARTICLE

Exploring team sensemaking in air traffic control (ATC): insights from a field study in low visibility operations

Stathis Malakis · Tom Kontogiannis

Received: 5 October 2012 / Accepted: 25 February 2013 / Published online: 7 March 2013

Abstract Sensemaking helps teams coordinate their efforts to understand and anticipate events in uncertain situations. While it is recognized that breakdowns in team sensemaking can lead to incidents, next generation air traffic management (ATM) projects have not paid serious attention to this research topic. This article presents findings from an exploratory field study of team sensemaking in air traffic control for low visibility operations. The study uses the critical decision method and the data/frame model of sensemaking (Klein et al. in Expertise out of context: proceedings of the 6th international conference on naturalistic decision making. Erlbaum, Mahwah, 2007) as a theoretical basis for examining Tower and Approach operations that will be transformed by next generation ATM projects. The findings concern the elicitation of explanatory frameworks for making sense of low visibility operations, the identification of domain-specific strategies that shape sensemaking and the presentation of emergent requirements for team sensemaking. Implications are made for embedding operational experience into future ATM systems to improve collaborative decision making.

Keywords Team sensemaking · Air traffic management · Data/frame model of sensemaking · Low visibility operations

S. Malakis (✉)
Hellenic Civil Aviation Authority, Rhodes/Diagoras International Airport, ATC Unit, Rhodes, Greece
e-mail: stathis.malakis@gmail.com

T. Kontogiannis
Department of Production Engineering and Management, Technical University of Crete, Chania, Greece

1 Introduction

The global air traffic management system (ATM) is facing growing demands for increased capacity, efficiency and safety. The International Civil Aviation Organization (ICAO) calls for a phased departure from current outdated ‘local’ operational concepts into a truly interoperable global ATM system with a time horizon extending up to the year 2025 (ICAO 2005). Two major ATM projects have been launched on both sides of Atlantic to examine the accommodation of increased air traffic capacity while maintaining good records of efficiency and safety. NextGen (Next Generation Air Transportation System) represents the U.S endeavor while SESAR (Single European Sky ATM Research) is the European equivalent. NextGen sets the requirements for the ongoing transformation of the National Airspace System in the US from a ground-based system of air traffic control (ATC) to a satellite-based system of ATM (FAA 2010). The implementation of NextGen is expected to allow more aircraft to safely fly closer together on more direct routes but would transfer many decision-making tasks from the ground facilities to the cockpit (FAA 2012). The transfer of decision making applies only for certain predefined situations in which technology solutions improve situation awareness of the flight crew that enables separation tasks to be transferred from ground to the flight crew. For example, during the climb into the en route airspace, the flight crew will be able to monitor the position of other aircraft with improved accuracy and thus, air traffic controllers will be able to assign separation responsibility to the flight crew as it climbs to its cruising altitude (FAA 2012).

On the other hand, SESAR comprises a set of interrelated projects specializing on trajectory management, reduction in airspace restrictions, new aircraft separation modes, system-wide information management, new automated functions to ease operator workload and 'best-in-class' operational procedures along with the development of new ones (SESAR-JU 2012). Both projects rely heavily on advanced technological solutions that will enable the sharing of timely, accurate and quality-assured information on a system-wide scale to all stakeholders. Moreover, it is recognized that the human operator will continue to play a central role, although with a notable shift of separation responsibilities from ground-based systems to flight decks.

Traditionally, human factors research in the field of ATM has centered on aircraft conflict detection (Kirwan and Flynn 2002), conflict resolution and human error classification (Shorrock and Kirwan 2002). This is not surprising since questions on how to avoid conflicts, how best to train controllers and how to support their tasks with automated aids have dominated the ATM system. While it is recognized that future ATM systems may have a profound impact on the roles, tasks and responsibilities of controllers, a recent literature review suggested that situation awareness and workload have been the most widely researched concepts (Langan-Fox et al. 2009); however, this research strand actually diverts attention from other human factors and organizational issues such as team adaptability to complex situations, re-allocation of tasks to controllers and pilots, large-scale team coordination and maintenance of air traffic competences. At first glance, SESAR and NextGen seem to address a wide area of emerging human factors issues, however, a closer look shows that both projects tend to focus on conflict management and the introduction of information technology so that conflicts are resolved in the flight deck rather than ATC operations rooms. Human factors issues in the NextGen project gravitate toward the human-automation interface to achieve an orderly introduction of NextGen in the National Airspace System (FAA 2012). On the other side of the Atlantic, the system-wide information management (SWIM) system will evolve to become a real-time repository and archive for all airspace information to promote comprehensive information exchange across all stakeholders. SWIM will support advanced automation, promote digital data sharing, promote common SA across all users and enable system-wide collaborative rerouting and other resource allocation functions. Although information sharing will be a positive change, controllers already experience high information load and it is crucial to determine what information should be available to controllers, as well as when and how to display that information.

Both ATM architectures present controllers with an incessant stream of information that calls for traffic monitoring, route optimization with lower separation minima and extension of normal operations into adverse weather; at the same time, controllers have to share tasks with ground and airborne technologies in reaching critical decisions. What remains unspoken is that controller abilities to attend to data streams, extract meaningful relationships and ultimately place data into a correct context are treated as greatly commensurate with the advances of information technology. The problem is exacerbated by an imbalance of information between flight crews and controllers which favors the former group in terms of traffic control and navigation.

Emerging uncertainty at all phases of flight control has been treated with the provision of more refined and timely information. It is expected, however, that research into how controllers make sense of data and information in uncertain situations can greatly benefit the control paradigms of the two ATM projects. Although the provision of more air traffic information may solve some uncertainty-related problems, it is doubtful that it can reduce breakdowns in coordination and communication (Bearman et al. 2010). In order to fully understand the potential effects of the introduction of new ATM systems, it is necessary to understand how the nature of controlling work may change in future (Hollnagel 2007). In a broader organizational perspective, Woods et al. (2002) argued that practitioners' abilities to make sense of the available information have improved much more slowly than anticipated. In a similar strand, Klein et al. (2007) pointed out that the most privileged purpose for practitioners may transcend the task of attending to the variety of stimuli in a situation and the task of making sense of how things are evolving to anticipate new events. In this sense, team sensemaking is an important aspect that should attract further research attention.

This article presents some insights gained from a field study of team sensemaking in Tower and Approach operations that could benefit next generation ATM projects. Findings regarding individual sensemaking have been presented in a companion article (Malakis and Kontogiannis 2012) which looked into cognitive maps as explanatory frameworks for making sense of traffic patterns and for reframing mental pictures. The purpose of this article is to investigate aspects of team sensemaking by using the data/frame theory (Sieck et al. 2004; Klein et al. 2006a, b, 2007) as a theoretical foundation. The fundamental claim of the data/frame theory is that situational elements can be explained only when they are adequately fitted into an explanatory structure or a frame that includes spatial (e.g., maps), causal (e.g., stories), temporal (e.g., plan) and functional elements (e.g., scripts). As Klein et al. (2007) stresses there is ample research literature on frames. Piaget (1954) and Minsky (1975) agree that the way people make sense of situations is largely shaped by cognitive frames that represent an internal representation of external reality. In particular, Minsky's account of a frame with slots, fillers and procedures is more closely aligned to our concept. In our account, we used the term frame to signify a synthesis of the earlier research. A frame can be defined as a structure (i.e., maps, stories, plans, scripts and combinations of them) that accepts information and put data into context. Klein et al. (2010) recognized that the data/frame model is a high-level abstraction that requires further studies and applications in order to provide a basis for pragmatic interventions. To this end, this study has undertaken three endeavors: (1) to elicit explanatory frameworks for making sense of demanding ATM operations (i.e., low visibility operations), (2) to document domain-specific strategies that shape team sensemaking and (3) to present a set of emergent requirements for sensemaking. The three endeavors have been pursued in alignment with an operational concept (i.e., low visibility operations) that is expected to be greatly transformed by the two ATM projects.

2 Team sensemaking

Teams of controllers work in an operational environment where tasks exceed individual capacity, decisions have multiple trade-off criteria, information uncertainty prevails, errors may have critical consequences and people lives depend on collective performance. Problems in team performance have been implicated in a number of high-profile aviation accidents—for example, the collision at Tenerife and the mid-air collision at Uberlingen. Until recently, research in ATM has addressed various aspects of team performance such as communication (e.g., Cardosi 1993; Morrow et al. 1993), information sharing with flight crews (Hansman and Davison 2000), situation awareness (Endsley and Smolensky 1998), mental models of controllers (Mogford 1997), team strategies during emergencies (Malakis et al. 2010) and aspects of error detection at team level (Kontogiannis and Malakis 2009). However, these aspects of team performance have been examined in isolation, hence, failing to get integrated within the context of team sensemaking.

Sensemaking has emerged as an important topic from the work of Weick (1995) which viewed sensemaking as a retrospective activity of individuals and teams bounded by organizational rules and constraints. Team sensemaking refers to the coordination of practitioners as they seek data, synthesize and disseminate their inferences in a team environment. According to Klein et al. (2010), the meaning of data becomes the object of negotiation which can trigger a new round of seeking more refined data, testing frames and replacing frames that proved incompatible with data. Team sensemaking is not a stand-alone concept but is related to other team concepts such as team adaptation, common ground and shared team models. Team sensemaking can be put into a meaningful perspective as an essential part of larger team models. For example, within the wider team adaptation model (Burke et al. 2006), team sensemaking corresponds to situation assessment as the team is engaging in recursive development cycles.

Sensemaking represents one of the key functions of *macrocognition* that can be accomplished by individuals, teams and organizations (Klein et al. 2003). Sensemaking is triggered as a response to situational surprises and failures of expectation. At the individual level, sensemaking starts when prior understanding is put in doubt and further attempts are made to integrate data into a better understanding of the situation. Sensemaking allows practitioners to understand how current accounts of the situation came about and to anticipate future evolutions through a process of fitting data into an explanatory framework (Crandall et al. 2006). Sensemaking is recursive and entails six cognitive processes namely: (1) identifying a frame, (2) questioning a frame, (3) comparing frames, (4) creating a new frame, (5) preserving a frame and (6) elaborating on a frame (see Fig. 1). To support the six processes of sensemaking, practitioners develop their own strategies through their accumulated expertise in a specific domain. In questioning a frame, for instance, Tower controllers develop rules for visual landmarks and set ‘tripwires’ to alert them when their estimates of a cloud base are no longer valid. Practitioners recognize when it is about time to start interrogating a plan by keeping track of events that should not be happening and wait for a predetermined time only. Klein (2004) refers to these alarming events as ‘tripwires’ that indicate that the plan may have some weaknesses or errors that need to be addressed.

Team sensemaking evolves in the ways that data are collected and synthesized, the checking of data quality provided by different members, the resolution of disagreements and the dissemination of information among the team. Characteristic team sensemaking behavior includes as follows: Data synthesis, Seeking data, Monitoring data quality, Resolving disputes and Dissemination of information and orders (see also Sect. 6 for details).

In comparison with individual sensemaking, teams employ similar cognitive processes but with different strategies and hence, different set of requirements and constraints (Klein et al. 2010). Our goal was to investigate team sensemaking in the ATM environment in a field setting. Specifically, this study has attempted to consider the central explanatory framework, the supporting strategies and the requirements for team sensemaking in the context of low visibility operations (LVOs) that are expected to change significantly in the next generation ATM projects.

Low visibility operations (LVOs) refer to aircraft operations at aerodromes during reduced visibility or low

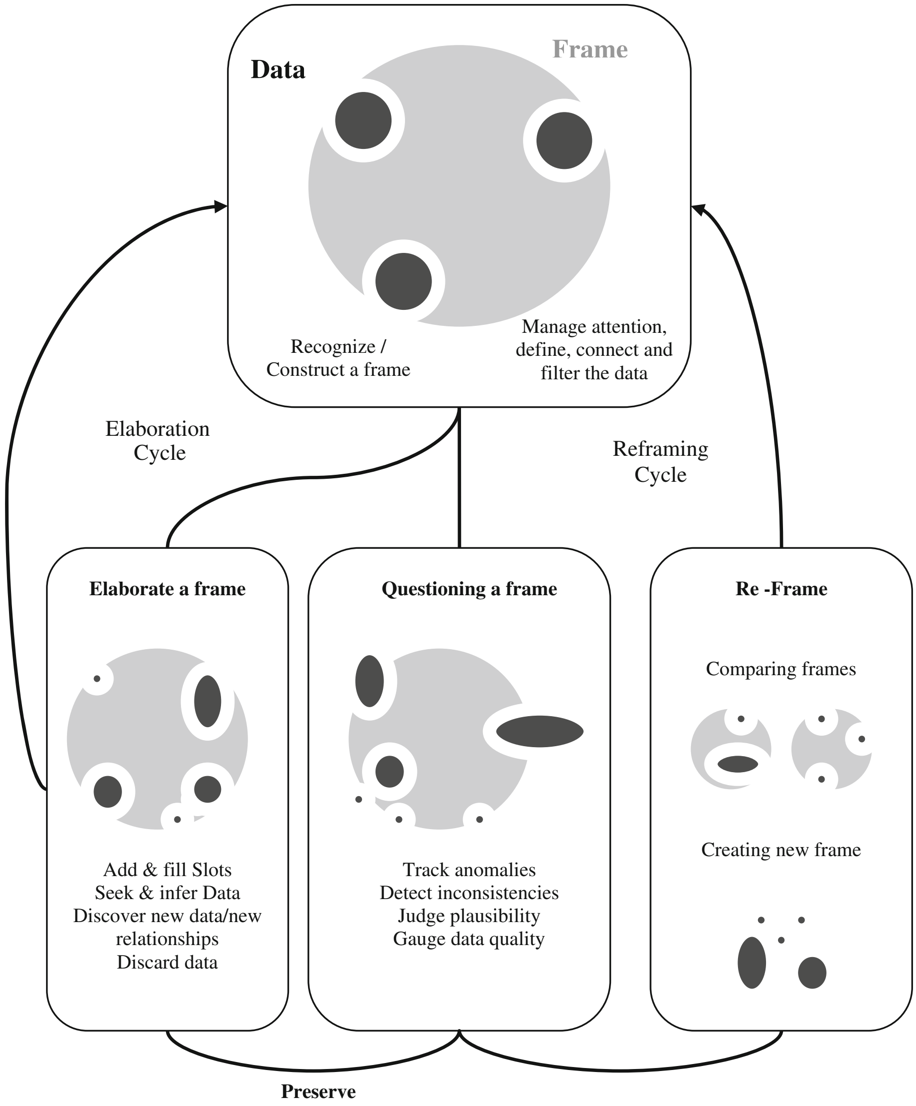

Fig. 1 Graphical depiction of the data/frame model (Klein et al. 2006b)

clouds conditions. LVOs can be divided into operations in the air and operations on the ground. We have focused on air operations during the approach and landing phases. Normally, the Approach controller routes arriving aircraft and provides navigation assistance so that the crew follows an instrument approach procedure (IAP) that will enable automatic guidance until the crew can visually acquire the runway and perform landing. The aircraft is transferred from Approach to Tower control when landing can be completed in visual reference to the ground, or when aircraft has reached uninterrupted visual meteorological conditions.

The tempo of operations may change significantly when there are conditions of low visibility or low clouds in the vicinity of the aerodrome. The aircraft follows an instrument approach procedure (IAP) until an altitude that breaks out of the clouds and the flight crew acquires visually the runway for landing. However, most IAP procedures terminate at a predefined height (called *decision altitude*) and the aircraft is expected to go-around if it reaches that height without having the runway in sight. Strict rules preclude flight crews from continuing below the decision altitude without a visual reference to runway (ICAO 2006). For example, if the decision height for an IAP is 200 ft and the cloud base is at 300 ft then the aircraft is expected to descend following navigational guidance for landing until 200 ft. Problems can emerge when visibility or other factors ‘blur’ the decision for a go-around. For example, with a cloud base diffusing at 240 ft, the flight crew descending at 210 ft may realize that they are about to break out of the clouds within a few more feet. Should they continue their descend assuming that they may break out of clouds at 190 ft or just reach 200 ft and execute a go-around? The problem may complicate further in cases where weather conditions deteriorate, flight crew limitations are at stake, on-board navigation systems may be malfunctioning, or a diversion to another aerodrome is ruled out due to minimal fuel conditions. The decision for a go-around in LVOs is a difficult one and may cause further delays and fuel consumption, especially in busy aerodromes. Meteorology officers, airport authority, ground handling staff, airport and airlines operations personnel may be part of distributed decision making during LVOs in larger aerodromes. In these cases, the decision process is much more complicated and involves many stakeholders. In smaller or seasonal airports, their role is minimal compared to air traffic controllers and flight crew members.

NextGen and SESAR are expected to enhance Tower and Approach operations by improving LVOs in two ways. First, the introduction of satellite navigation systems will enable approaches with lower minima during adverse weather conditions. Second, the introduction of synthetic vision in the cockpit will provide crews with terrain imagery and position/attitude information for use in low visibility conditions. The implementation of these systems will reduce airport capacity gaps during low visibility conditions from 50 % in 2008 to only 20 % at 2020 (SESAR-JU 2009). In the context of NextGen, FAA started to implement an incentive policy where aircraft equipped with enhanced flight visibility systems can continue their approach below minima and gain privileged access to airports.

3 Research setting

Our research setting was a medium level European airport with seasonal traffic. In low-tempo operations, work-shifts comprised two controllers in the Tower and the Approach units. In medium traffic, shifts comprised one controller in the Tower unit and another two controllers in the Approach unit (i.e., the executive and planning controllers). The executive controller was responsible for direct control of aircraft in the terminal area and for implementation of the overall plan that was established by the assisting planner. In high-tempo operations, shifts comprised four to five controllers split in the Tower and Approach units. The supervisor was the most senior controller and was located at the Tower or Approach unit, assuming control in cases of staff shortage.

The aerodrome control tower is the unit where a flight begins and terminates. As defined by ICAO (2007), an aerodrome tower is an ATC unit established to provide air traffic control service to aerodromes. The area of responsibility (AoR) of a TWR is an Air Traffic Zone (ATZ) with the shape of a cylinder with usual dimensions of 5 Nm radius and 2,000 ft in height. The ATC functions of a control tower are normally performed by two control positions:

- *Aerodrome controller* Responsible for operations on the runway and the aircraft flying within the AoR of the aerodrome control tower.
- *Ground controller* Responsible for traffic on the maneuvering area with the exception of runways.

The main operational function of Tower Controllers is defined by ICAO (2007). The Aerodrome Controllers shall issue information and clearances to aircraft under their control to achieve a safe, orderly and expeditious flow of air traffic and in the vicinity of an aerodrome with the objective of preventing collision(s) between:

- aircraft flying within the designated AoR of the control tower, including the aerodrome traffic circuits,
- aircraft operating in the maneuvering area,
- aircraft landing and taking off,
- aircraft and vehicles operating on the maneuvering area,
- aircraft on the maneuvering area and obstructions on that area.

ICAO (2007) defines the maneuvering area again as the part of the aerodrome to be used for takeoff, landing and taxiing of aircraft, excluding aprons. There is also the movement area, which is the maneuvering plus the apron. ICAO clearly states that only the maneuvering area belongs to the jurisdiction of Aerodrome Controllers.

The APP is the second ATC unit for departing aircraft or the penultimate for the arriving ones. As defined by ICAO (2007) an APP is a unit established to provide ATC service to controlled flights arriving at or departing from one or more aerodromes. The AoR of an APP is a TMA with the shape of cylinder with usual dimensions of 60 Nm radius and 18,500 ft height. The ATC functions of an APP unit are normally performed by two control positions:

- *Executive controller* Responsible for the direct control of aircraft in his/her AoR and for carrying out the overall plan established by the Coordinating Controller.
- *Coordinating controller* Responsible for establishing the overall plan for the entry and exit of the aircraft in the AoR and assist the Executive Controller in his/her tasks.

4 Method

The present study has looked into aspects of team sensemaking at low visibility operations (LVOs) using the critical decision method (Crandall et al. 2006) to probe into complex cognitive tasks such as, exploration of subtle cues, development of expectations and expertise, and evolution of cognitive strategies. A previous study explored the extent that cognitive maps, or mental pictures, provide an explanatory structure in the data/frame theory as they may represent several spatial, temporal and functional relationships in a frame (Malakis and Kontogiannis 2012). CDM involves multiple cycles of retrospection into recalled incidents guided by probe questions (Hoffman et al. 1998) structured by four interview phases that examine the challenges faced by practitioners in four 'sweeps':

1. Identification of challenging incidents that help to elicit discoveries about cognitive phenomena
2. Creation of incident accounts and timelines with emphasis on critical decisions
3. Elaboration of strategies employed by practitioners to reach decisions
4. Probing on 'what-if' questions to elicit differences between experts and novices.

Although some limitations have been reported (e.g., reliability concerns due to retrospective accounts and memory distortions), the CDM method has been extensively applied in human factors because it guides practitioners to elicit their strategies for novel and non-routine events (Hoffman et al. 1998). To counter the method limitations, we relied on direct observations of traffic control and unstructured interviews with controllers at an operational setting. We investigated cases of teams making sense of information in LVOs when there was a growing suspicion about the current situation, or there was a sudden surprise, or the situation at hand was unclear.

Eleven operational controllers holding Terminal Approach Radar Control Ratings participated in the study with expertise ranging from 4 to 12 years. All controllers were also holding valid Tower and Approach procedural (non-radar) ratings. Our aim was to conduct CDMs in order to build a corpus of data about team sensemaking targeting at LVOs. To this end, we conducted 18 CDMs for cases that we had access to the accounts of all team members that were present during the most informative LVO events. CDMs were conducted on those cases in which events unfolded in unanticipated ways. Each CDM lasted for about 1 h, notes were taken, a sketch of incident was made in the form of episodes and usually it involved one controller although in a few cases two or more controllers were present (i.e., the case study of Sect. 7). Eventually, we elicited 18 cases describing incidents in which controller cognitive strategies were stressed by growing suspicious about the turning of events, sudden surprises were encountered, operational procedures were tested to their limits and situations remained unclear well after critical decisions were made.

Research approaches usually make the difference between a fragile and a resilient assurance in exploring team sensemaking. In designing our approach, we have been overly conservative as we focused on a well-defined segment of ATM operations (i.e., low visibility operations) and employed several cognitive tasks analysis methods. For example, the behavioral markers (Table 1) have been selected through a process of cross-checking CDM data, observational data in adverse weather conditions and unstructured interviews. By interacting with controllers, we tried to elicit their explanatory frameworks as presented in the data/frame model (Klein et al. 2007). In our study, the altitude band of the cloud base emerged as a central explanatory framework. This very fact may be of some value to future research as it reveals the presence of a network of *if–then* rules that provide a basis for estimating vertical visibility and enable controllers to get accurate CBA estimates. Although similar rule networks have been reported for weather forecasters (Hoffman et al. 2006), their application to ATC controllers has not been investigated in the literature.

5 Explanatory frames and sensemaking strategies

Data collected from CDMs were further analyzed to elicit explanatory frames employed by ATC controllers and examine strategies supporting the six processes of sensemaking. The central element of the organized structure that emerged as a frame for team sensemaking was the 'altitude band' in which controllers were expecting the aircraft to break out of the clouds and complete the approach to land (referred to as *Cloud Base Altitude*, CBA). The altitude band was expressed as vertical height (e.g., 300 ft), as upper and lower limits (e.g., between 300 and 400 ft) or as an upper limit (e.g., less than 200 ft). Figure 2 also shows the *decision altitude* at which aircraft have to initiate a go-around procedure if visual reference with the runway is not made.

The explanatory framework is the foundation of the data/frame theory as it is the structure used to perform all the functions and explain the data (Klein et al. 2007). In our case, the explanatory frame included the CBA estimates as well as complementary information about decision altitudes, meteorological reports, knowledge of local weather patterns, visual landmarks, flight crew reports and hand-offs from previous shifts. This section presents an account of how controllers make sense of low visibility operations (LVOs) using CDMs with experienced controllers. The last part of this section summarizes several strategies that support sensemaking such as, gauging data quality, setting visual tripwires, anticipatory thinking and preserving resources for new events.

Based on Fig. 1, a detailed analysis of the six processes of sensemaking is provided on the next subsections.

Table 1 Team sensemaking strategies and associated behavioral markers

Sensemaking processes	Strategies and associated behaviorial markers
Identifying a frame	Tower and Approach Controllers receive routine meteorological reports and formulate an initial altitude band for the cloud base that will be tested by observing the first approaching aircraft
	Tower controllers employ their own network of rules regarding observability of visual landmarks to estimate an altitude band for the cloud base
	Approach controllers are informed about visual tripwires set by Tower controllers concerning limits of the altitude band
	Tower controllers check the altitude readings of the radar against the visual tripwires when the first aircraft breaks out of the clouds to verify altitude band
	Flight crews are requested by Tower controllers to provide an accurate report of the cloud base; Approach controllers are informed accordingly
	The team supervisor agrees on the initial altitude band that will be held until changes are required; controllers set their operational tempo and back up plans accordingly
Questioning a frame	Tower controllers form rules for visual tripwires based on expertise to alert them that their current altitude band is no longer valid
	Controllers voice any discrepancies derived visually or by radar in the approach path of the aircraft that may indicate a need for change (e.g., cloud base is diffused or ragged or fluctuating rapidly, deviation of an aircraft from the final approach track)
	Controllers discuss meteorological information that may trigger a revision of the altitude band
	Controllers discuss information derived from the flight crew of an approaching aircraft that may trigger a revision of the altitude band
	Tower controllers monitor and discuss with colleagues 'what-if' scenarios (e.g., the possibility of a go-around) in relation to the selected altitude band
Reframing : comparing frames	Controllers suggest, negotiate and compare altitudes band and decide for one
	Team supervisor combines and synthesizes contrasting viewpoints
	Team supervisor decides on whether to modify or await new information to arrive before ending the comparison phase
Reframing : creating a new frame	Tower and Approach controllers voice modifications in the altitude band
	Team Supervisor synthesizes competing altitude bands into one
	Controllers set revised tripwires for the new altitude band
Preserving the frame	Small variations in CBA estimates are attributed to transient weather phenomena and the type of the aircraft (e.g., size of aircraft & height of the cockpit above ground)
	A single go-around is attributed to other factors (e.g., non-stabilized approach due turbulence) not related to the visibility conditions and cloud base
	Routine meteorological information, in combination with visual observation, is used to preserve the currently used altitude band
	Information derived from the flight crew is used to preserve the currently used altitude band
	Team supervisor decides on continuing operations with the current altitude band
Elaborating a frame	Controllers discuss new information to fine tune the altitude band (e.g., changes in the type of cloud formation, darkening of clouds, changes in wind speed)
	Meteorological officers are engaged in the discussion for the modification of the altitude band with the controllers' team
	Controllers collaborate to discover relationships (e.g., based on operational knowledge and *if–then* rules network) between information derived from all sources that preserve and extend the current altitude band

5.1 Identifying a frame

In most cases, identifying an altitude band (i.e., a frame) was an effortless process and no deliberate sensemaking was required. When handling familiar LVOs scenarios, controllers were observed to resort to pattern matching. Controllers typically managed to get good CBA estimates by synthesizing information about previous aircraft approaching to land in low visibility conditions. This was mostly the case where weather conditions were stable, or when changes in weather patterns were gradual and predictable. Apart from meteorological reports, controllers had a rough idea based on their expertise on local weather phenomena and visual observations from the Tower unit. It appeared that Tower controllers were using prominent landmarks (e.g., buildings and hill tops from the

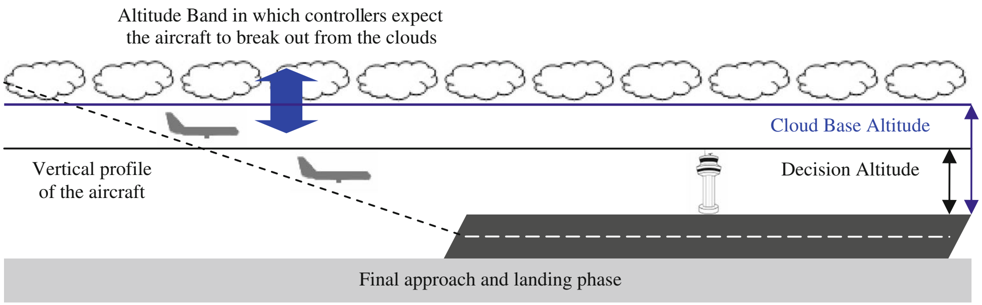

Fig. 2 A graphical depiction of the altitude band at which the aircraft was expected to break out of the clouds during the approach

surrounding area) and were setting visual tripwires to make predictions of the altitude band.

In essence, the visibility of the surrounding landmarks was used as an ad-hoc network of affordances to meet the complexities of LVOs. Affordances should not be seen as attributes of artefacts per-se (e.g., operational procedures) but as ad-hoc supports of practitioner goals in the context of unfolding situations. In our study, controllers went beyond the prescriptions of artefacts and created a nuanced network of *if–then rules* that signified their level of expertise (e.g., if I can see A but I cannot see B and it is raining then the cloud base should be at around X).

Information about the first aircraft to approach was also used to make initial CBA estimates as controllers could see in their radar the altitude at which aircraft was breaking out of the clouds. This expectation was tested against previous approaches and personal knowledge (i.e., their data-store of rules). During the approach, Tower controllers were monitoring the altitude of the aircraft from the radar display and were checking the altitude at which the aircraft was breaking out of the clouds; this is roughly the same altitude from which the flight crew could 'see' the runway. Controllers were expecting that the next arriving aircraft would also break out of the clouds at about the same altitude with a few minor variations (e.g., due to wind direction, the presence of rain). In typical scenarios, pattern recognition led to the selection of appropriate CBA frames (see recognition-primed decisions in Klein 1998). Subsequently, Tower controllers would pass the CBA information to Approach controllers in order for the latter to refine their vectoring and instruct other flight crews that would arrive later.

5.2 Questioning a frame

Frames provide controllers with modicums for expectations. When encountering data that violate their expectations, controllers would initiate a process of challenging the plausibility and the quality of data they receive. Questioning a frame becomes more difficult at a team level, as Weick (2007) pointed out in many high-profile cases where 'questioning the frame' failed with grave consequences. Typical triggers for questioning the CBA frame included aircraft that were not breaking out of the clouds at the expected altitude, difficulties in direct visual observation from the Tower unit although flight crews were able to see the runway at the expected altitude band and finally, violations of *if–then* rules regarding visibility estimation. In these cases, controllers relied on flight crews and managed to refine the altitude band without being able to visually observe it.

In questioning a frame, controllers could not know whether their frame was incorrect or the situation took a sudden turn. The violation of their heuristics could qualify as novel cases to be added to their knowledge base. The first aircraft that reported having in sight the runway—although the runway could not be seen from the tower—would trigger a questioning of the frame as controllers were not able to cross-check the CBA visually. As a result, the planning horizon of controllers would be reduced (e.g., handling only one aircraft at a time) because the possibility of a go-around procedure and the need for constant verification would increase. Hence, controllers were becoming more sensitive in tracking anomalies (e.g., crew differences in the altitude at which the runway was in sight), in detecting inconsistencies (e.g., meteorological reports) and in gauging the data quality (e.g., flight crews versus meteorological officers). These strategies were supported by their own network of rules and their collaboration with experienced colleagues and supervisors.

5.3 Reframing: comparing multiple frames

Practitioners may track up to three frames simultaneously, with the usual case involving two frames (Klein et al. 2007). Having two or even three explanatory frames requires a mechanism for ultimately settling on only one. Comparison of multiple frames can be initiated by the detection of an anomaly that resembles the function of a bifurcation point (i.e., an unstable, temporary state that can evolve into one of several stable states). However, the direction of change is not clear and extensive expertise is required to track down the possible states.

In our study, when confronted with uncertainty, controllers were comparing multiple frames in terms of possible explanations of the data at hand. In general, reframing was triggered by deviations from expectations (e.g., a changing weather, an aircraft executing a go-around) and by crew reports that contradicted their network of *if–then* rules. In these cases, controllers had to choose between a temporal change in vertical visibility that affected only one aircraft and a more permanent situation that indicated a deteriorating situation that could lead to closure of the airport. Additionally, Tower controllers had to convey their judgment to Approach controllers so that they could plan for later traffic accordingly. Planning the sequence of approaching aircraft is more difficult when having to divert inbound aircraft to alternate airports than when having to stack aircraft into a holding pattern near the airport awaiting weather improvement.

5.4 Reframing: creating a new frame

This is not an easy option as it implies aborting a current account and constructing a new one that was not an option in the first place. This process is quite similar to replanning where a whole network of tasks has to change in a restricted time window which implies changes in coordination task between Tower and Approach controllers. Kontogiannis (2010) argued that replanning requires modifying a plan during execution which presents many challenges to teams working in situations of high uncertainty. Replanning involves re-interpreting the situation and re-assessing the impact of events and actions on established goals and team functions.

Similarly, the creation of a new frame imposes strong demands that may render the process difficult. Controllers face many challenges in choosing between a temporal visibility disruption to the approaches of one or two aircraft and an extended period of low visibilities that will last for several hours because this requires a good knowledge of weather patterns; it also required forecasts in which replanning of the air traffic becomes a critical factor. In our study, replanning was supported by a loose-coupling tactic (e.g., extending the miles on trail between successive arrivals) and by preserving an airspace volume that could be used for holding aircraft. In addition, team supervisors resorted to proactive coordination with neighboring airports to decide on the number of aircraft to accommodate in cases that a diversion was required. This anticipatory action was effectively reducing their workload in the case they had to divert aircraft and allowed them to focus attention on each approach. In this way, they could easily accommodate disruptions due to reduced visibilities that would delay aircraft landings.

5.5 Preserving the frame

When controllers preserve a frame by explaining away inconsistent evidence, there is a risk of fixation errors (De Keyser and Woods 1990). In safety critical systems, misleading cues, absent indicators and unusual cue patterns may create an environment that impedes error detection (Kontogiannis and Malakis 2009). Sometimes preserving a frame may be the result of fixation errors and explanations may be completely out of focus. Small variations in CBA estimates may be contributed to wind conditions rather than deteriorating weather patterns with a risk to aircraft approaches. Also, small discrepancies in the network of rules about visibility may be explained away by visual distortions due to lightning conditions and rainfall or may be overruled by the team supervisor. In our study, the most interesting cases regarding preservation of the frame were ‘forced’ by flight crew perceptions of CBA that run contrary to controller expectations (e.g., see further discussion in the incident presented in Sect. 7).

5.6 Elaborating a frame

This process involves preserving the current frame by adding more details and by filling in missing slots. The chances of surprises or inconsistencies are minimized as more details are added in due course. Normally, elaboration is one of the final steps of the sensemaking process and signals a period of frame stability. In essence, practitioners make minor calibrations in their account as new data fit the frame conveniently. The drive for new data is smooth and observed patterns are progressively familiar.

For example, a typical case concerned the passing of a thunderstorm cell over the airport which caused visibility to drop to zero for less than 15 min and then increase gradually. Tower controllers would observe the incoming cell storm visually and constantly check their own visual landmarks in order to advice Approach controllers to hold the aircraft for weather improvement or get an estimate of which aircraft would have to ‘go around’. Finally, when the storm cell was well clear of the airport, Tower controllers were the first to observe the gradual increase in visibility by checking their visual landmarks and advised Approach controllers to resume operations by exiting aircraft from the holding stack.

5.7 Behavioral markers for team sensemaking strategies

The six processes of team sensemaking are supported by domain-specific strategies developed by practitioners through accumulated expertise. We elicited several sensemaking strategies such as, pattern matching, setting triggers for questioning a frame, gauging data quality, anticipatory thinking, preserving resources for contingent events, trading off loose and tight control actions, and so on. Although derived from ATC, in principle, most sensemaking strategies seem to be consistent with other application domains (e.g., Klein et al. 2010). Strategies employed by experienced controllers to support the six processes of sensemaking have been discussed in Sects. 5.1–5.6 and are listed in Table 1.

Behavioral Markers can be defined as taxonomies of key non-technical skills associated with effective, safe job performance in a particular job position with some decomposition of major skill areas (e.g., decision making) that are usually illustrated by exemplar behaviors. The main characteristics of behavioral markers are the following:

- Observable behaviors of teams or individuals
- They are derived from data analysis from various sources
- They are describing specific observable or inferred behaviors and not personality characteristics
- They do not have to be present in all situations
- They employ simple and domain-specific phraseology

Sensemaking strategies are cast as behavioral markers in Table 1 rather than as generic psychological descriptions. For instance, 'preserving resources for contingencies' is expressed as 'preserving an airspace volume for holding aircraft'. Also, 'triggers for questioning a frame' are specified as 'violation of *if–then* rules' and 'aircraft breaking out clouds at unexpected altitudes'. It was easier to use behavioral markers from the corpus of CDMs and the data from direct observations and unstructured interviews. We divided each incident into episodes corresponding to the sensemaking processes in order to elicit and classify the strategies employed and the associated behavioral markers. Then, we organized the strategies by grouping them and cross-checking them by visual observational and unstructured interviews. Only when all sources agreed, did the classification proceeded. The disadvantage of this approach is that some behavioral markers may not be clearly distinguished as features of specific strategies. We expect that follow-up studies would perform a fine tuning of behavioral marker descriptions and assign them clearly onto psychological strategies.

6 Team sensemaking requirements

Team sensemaking differs from individual sensemaking in the ways that data are collected and synthesized, the checking of data quality provided by different members, the resolution of disagreements and the dissemination of information among the team. The processes of the data/frame model of sensemaking rely on certain task and team requirements with regard to the collection, integration, verification and dissemination of information among the team members. These requirements mostly stem from the collective nature of work in the ATC environment and are discussed in this section.

6.1 Data synthesis

Synthesizing data from several sources remains the primary responsibility of team supervisors who have to collect data from physically remote areas such as, the Tower and Approach units. Tower controllers can provide a more complete picture of CBAs that can be promptly verified by visual means and flight crew reports. Supervisors can monitor the voice loops between Tower controllers and flight crews which support a better understanding of the situation but radiotelephony congestion often renders the monitoring process rather difficult or even distracting. On the other hand, Approach controllers can provide supervisors with rough CBA estimates (e.g., altitude is displayed in increments of 100 ft every 4 s on the radar screen). This creates a dilemma for team supervisors, that is, whether to stay in the tower area (where a privileged view of the unfolding situation is obtained) or move to the approach area (where better coordination is achieved for holding and re-routing aircraft). Establishing voice loops among practitioners in order to build a common stance and schedule tasks is also a common practice in many other command and control environments (e.g., see space shuttle mission control in Patterson et al. (1999). Team supervisors have the added task of deciding when to proceed with the data at hand or wait for new data, but they were more confident in their judgments as they had a more nuanced network of *if–then* rules.

Approach controllers had a more difficult job in the synthesis of data than Tower controllers because of their higher workload and communication interruptions. LVOs are associated with adverse weather which increases the workload of Approach controllers because the flow of approaching aircraft is disrupted by the need to circumnavigate aircraft from areas of active weather, preserve critical airspace for holding stacks and work with extended separation minima. Data synthesis becomes more difficult in the Approach unit because additional information coming from verbal exchanges between controllers and pilots in the Tower area may be missed out due to increased communications and interruptions imposed by the adverse weather.

6.2 Seeking data

Seeking data is usually the job of individual controllers who often have to coordinate with each other to overcome problems of missing data, unreliable data and unconfirmed data. In the data/frame theory, the explanatory framework drives the seeking of data that governs the revision of frames (Klein et al. 2006b). Hence, controllers build their own explanatory frames so that their search is not too broad or narrow or vague. Their explanatory frames are complemented by the team supervisor who provided them with ideas where to look for data and how the data are connected together. Although controllers have clear job responsibilities, their roles in seeking and synthesizing data are often blended. For instance, the supervisor may not only synthesize data but also have some good ideas where to look for useful data. Again, individual controllers seek data on the basis of their understanding of the situation that is built from their own frames.

The activity of seeking data takes different forms according to the responsibilities of different practitioners. For instance, Tower controllers could seek data from direct observation, the radar and routine meteorological reports. However, they would mostly rely on direct observation and set visual tripwires to alert them about the visibility conditions by referring to prominent landmarks that surround the aerodrome; they used the radar data in a secondary role to cross-check possible CBAs. In contrast, Approach controllers utilized a combination of radar data and monitoring voice loops between the Tower and the flight crews. Direct telephone communications between Tower and Approach controllers were used to bridge the gap of physical distancing and the inability of the Approach controllers to physically observe the unfolding weather conditions. Finally, team supervisors had a central role in directing data search, especially when located in the Approach area. The most usual pattern involved supervisors establishing a policy of frequent reports from Tower controllers which directed further search for data.

6.3 Monitoring data quality

Data synthesizers have to assess the quality of the data in terms of their credibility and relevance or recency. Monitoring of data quality has to take into account the experience of the controller, the reliability of reports and radars, and the delays in getting the necessary information. For instance, both Tower controllers and meteorologists could assess a cloud base but their estimates differed as the Tower building was 30 meters above the meteorology office, hence changing their observation angles. However, direct observation was supported by declarative knowledge which allowed practitioners to improve their final judgment of the CBAs. In daylight conditions, meteorology officers formed a semi-official system of CBA estimates founded on the observation of prominent landmarks and meteorological variables (e.g., if barometric pressure is decreasing and I can see A and dew point is X and cloud concentration is Y and the relevant humidity is Z then cloud base should be W). Other weather forecasting strategies have been described by Hoffman et al. (2006) who focused on what it takes to reach the top of this field. Tower controllers employed a similar referential system but their landmarks were different because of their own training and because of their different observation angles. Although the two systems had their own advantageous points of view, it was the flight crew reports that were the most valid CBA estimates; however, this argument was in trouble in some incidents as illustrated in Sect. 7.

The limited experience of trainee controllers was another factor that affected the quality of data. In the Approach unit, team supervisors would tend to question the data of inexperienced controllers from the Tower unit in terms of the altitude band of the cloud base in order to get a more accurate picture and to find any estimation errors made by junior team members. Moving directly to the Tower unit to collect the necessary data themselves was not their preferred option as it could be interpreted as indirect questioning of the credibility and professionalism of the junior members. Therefore, apart from identifying relevant risk factors in the quality of data, data synthesizers should develop socially acceptable methods for cross-checking their data.

6.4 Resolving disputes

In teams, different practitioners may develop different account of events or favor different frames of explanation. In questioning a frame, for instance, junior members may notice weak signals but fail to mention these to the rest of the team. Similarly, in comparing frames, team members may take different perspectives of which frame is most accurate. Disagreements can be resolved through several means such as, hierarchical authority and pressure for consensus. In our study, disagreements and conflicting perspectives were resolved mainly through the team supervisor and the final observation of the approach taken by aircraft. Hierarchical authority and flight crew reports had the final word through a process of elaborate testing and revision. For example, a difference in CBA estimations between Tower controllers and meteorology officers was resolved by the reports of the last aircraft to land. In the absence of such reports, the supervisors made a decision based on a synthesis of data as well as a negotiation with controllers and meteorology officers. It is noted that senior controllers treated an accurate CBA estimate as a form of professional pride that kept the team coherence intact.

6.5 Dissemination

Dissemination of information and orders usually follows the selection of an explanatory framework for making sense of the situation. Dissemination involves both verbal communications and written reports about the situation or means to control a problem. Klein et al. (2010) have reported that military teams are quite stingy with their dissemination—for example, orders may change the sequence of actions, reference to older orders may be missing, or the rational for a change may be vague.

Controllers need to communicate with pilots directly using voice communications or indirectly using data links. Normally, for the purpose of air-ground voice communication very high frequency (VHF), systems are used. High-frequency (HF) and ultra-high frequency (UHF) systems can also be utilized in certain cases and geographically constrained areas. Data links are also used for air-ground information exchange. Each ATC unit has been assigned a set of discrete frequencies that enable Controllers from this unit to communicate with aircraft under their AoR, using standard (RTF) Radiotelephony procedures. Controllers also need to communicate with other ATC units or services. For this purpose, ground voice and data communications networks have been installed that enable them to communicate with their neighboring and virtually with any other ATM facility in the world using the Aeronautical Fixed Telecommunications Network (AFTN). The communications systems are managed through dedicated panels of the CWPs. The voice/data communication between adjacent ATC units is also standardized and conducted normally in aviation English to prevent ambiguities. The VHF RTF communications are characterized by a major shortcoming. Pilots and Controllers cannot use the same frequency simultaneously because when one is transmitting the other is receiving and vice versa. Thus, Controllers and pilots cannot transmit and receive simultaneously. Even though this inherent technical shortcoming is well known and properly documented, it remains a cause of aviation incidents and accidents. NextGen and SESAR are expected to resolve these shortcomings by improved the quality, timeliness and accuracy of both voice and data communication.

In our study, dissemination of information between controllers, flight crews and meteorology officers was quite accurate based on an operational language that was concise, clear and meaningful. Controllers were able to appreciate major attributes of information (i.e., criticality and timelines) and were able to judge the level of workload and interruptibility of other team members; as a result, Tower controllers were not distracted by Approach controllers with redundant requests for verifying the altitude band in critical phases of Tower operations. In some cases, however, verbal reports from flight crews were delayed or were offered in a piece-meal fashion that made difficult the integration of data in the control room. Such cases were more frequent when flight crews had to attend to several emerging issues due to adverse weather conditions.

7 Case study: seeing the runway through the clouds

The cognitive flow of team sensemaking is a challenging issue that requires a tedious introspection of the thinking and reasoning of controllers. Capitalizing on the accounts of two controllers that were elicited during CDMs—as well as the traffic control experience of the first author—the following event provides a context for looking into the flow of strategies (Table 1) that shape team sensemaking in low visibility operations. This particular incident was selected as it fits all categories mentioned earlier namely: growing suspicious about the turning of the events, encountered sudden surprises, operational procedures tested to their limits and situations remaining unclear well after critical decisions were made.

7.1 Identifying a frame

A team of two controllers was on duty on a winter afternoon shift. The most senior member, who was formally the team supervisor, assumed the Approach duties while the less experienced one assumed the Tower duties. The weather started to deteriorate quickly and a squall line of thunderstorms from the northwest was expected to hit the aerodrome toward the end of the shift. It is worth noting that the instrument landing system (ILS) was working but it was declared non-operational due to construction work on the runway (i.e., new measurements were required to tailor the length of the runway to the ILS vertical guidance). The instrument approach procedure currently in use was based on the Terminal VOR procedure that provided higher decision minima than the ILS procedure. The team supervisor was concerned with this fact because the decision altitude of the terminal very high frequency omni-directional range (the T-VOR procedure indicated 1,100 ft) was much higher than the one indicated in the ILS procedure (i.e., 220 ft).

Based on the forecasts and the radar picture of the approaching squall line, the supervisor initially estimated that the cloud base would become lower (i.e., well below 1,800 ft). He was awaiting the final arrival in his shift, a short scheduled flight of a turboprop aircraft from a nearby airport. As he expected that the aircraft will arrive at about the same time that the squall line of thunderstorms hit the airport, he informed the flight crew at the nearby island that a thunderstorm would soon arrive in the destination airport; the crew agreed to expedite the procedures and requested vectoring after takeoff from the nearby airport to avoid areas of active weather. Throughout the shift, the Tower controller was reporting that the clouds base was constantly lowering as he could it check visually and verify it with the arriving aircraft. At the time the turboprop aircraft departed from the nearby airport, the supervisor received a report that the cloud base was descending below 1,400 ft. He chose to vector the aircraft from the east side of the island (see solid line in Fig. 3) instead of the normal west side (see dotted line) and placed it for landing before visibility dropped below 1,100 ft. Controllers expected to outrun the squall line and land the aircraft within limited time and through marginal visibility. The supervisor expected the CBA would be in the range of 1,100–1,200 ft at the time the aircraft was on the final approach for landing. This was his initial frame which enabled the flight crew to complete the approach with a landing in marginal conditions.

7.2 Questioning the frame

Since the supervisor assumed control, the aircraft was given a series of vectors to shorten the route and remain out of areas of turbulence that were extending many miles beyond the area of active weather cells. The aircraft was flying at a high speed and the flight crew was frequently requesting weather updates of the destination airport. Half time into the flight, the supervisor saw in his radar the active weather cells moving fast closer to the airport than he had anticipated. At the time the aircraft was given the final vector to establish the final approach track (see Fig. 3, northeast corner), the Tower controller was unable to visually see the runway edges while the rainfall was intensifying.

When the aircraft was established on the final approach track and started its approach to land, the Tower controller was unable to see any part of the runway and judged that the CBA would be below 200 ft. The meteorology officer reported at the same time that the storm cells were over the station. The supervisor was now considering that the cloud base would be lowering below 1,100 ft on the basis of a heuristic learned from experience (i.e., when the tower cannot see any part of the runway and it is raining then the cloud base is located well below 220 ft which was the decision altitude in the ILS procedure). As the aircraft was following the TVOR procedures (i.e., a decision altitude of 1,100 ft), the supervisor decided to inform accordingly the aircraft and initiate a contingency plan in the case of a go-around. His expertise indicated that the cloud base was preventive for a TVOR approach as the storm cells would need another 10–15 min to pass over the aerodrome. Upon receiving this weather update, the crew decided to continue the approach until the minima of the TVOR approach (i.e., 1,100 ft). They reported that they were inside the clouds with zero visibility and they will be continuing their approach until the decision minima of the procedure.

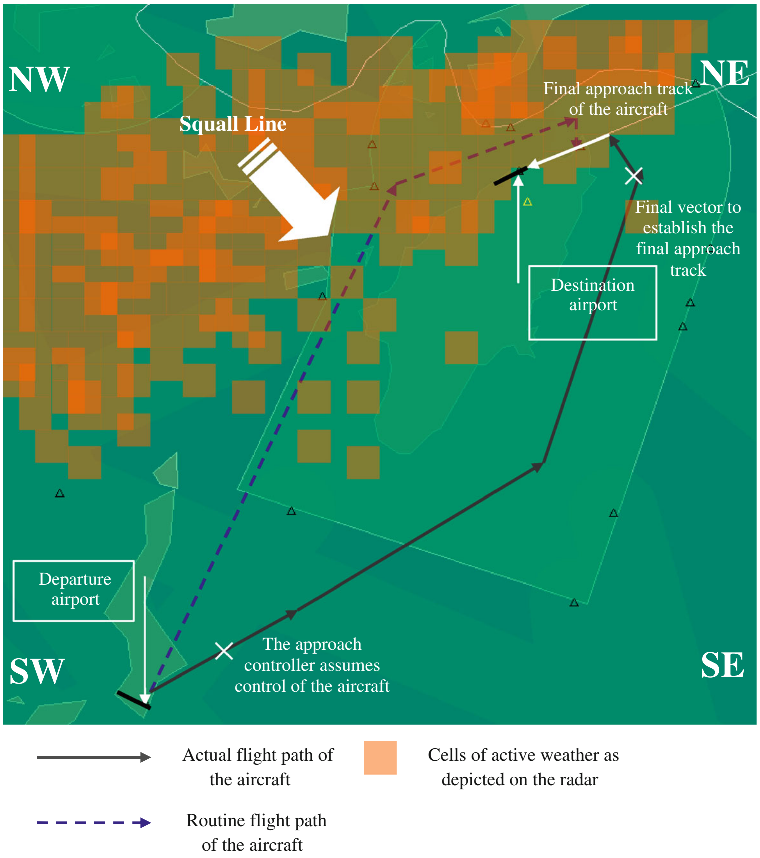

Fig. 3 A graphical depiction of flight of the aircraft prepared on the unit's simulator

7.3 Reframing: comparing multiple frames

The team supervisor now had to compare two frames. The most likely frame was that the cloud base was well below the 1,100 ft limit which would require a go-around. The less likely frame assumed that an opening could be found in the clouds (or the clouds would be diffusing) that would allow the crew to continue their approach and land. The first frame entailed planning for a go-around and making a decision where to divert the aircraft. The fact that the aircraft was a turboprop model (which was unable to climb higher than the storm clouds) presented many challenges since the most suitable airport for diversion was the one that the aircraft had previously departed from; however, this airport had no radar and the weather was getting worse. Another suitable airport was 150 Nm southwest but it was unclear if the aircraft had enough fuel to fly there, circumnavigating the active weather. The team supervisor had one more weather update and predicted that a go-around and a complex diversion were imminent. The Tower controller reported that he could see neither the runway and the taxiways nor even the apron which was right below the tower.

7.4 Reframing: creating a new frame

The aircraft started its descent and the flight crew reported that they could see the runway at 1,200 ft. The supervisor requested confirmation that they could see the runway and received confirmation. He seemed puzzled but transferred the aircraft to the Tower controller and instructed him to confirm again that the flight crew had the runway in sight before issuing a clearance for landing. Subsequently, the supervisor focused on his radar screen and checked for even slightest deviations in the path of the aircraft that could signify the need for a go-around. He was thinking that the CBA would be at about 1,200 ft and that visibility conditions in the tower area would prevent any visual checking. The aircraft completed its approach and landed uneventfully while the Tower controller reported seeing the lights of aircraft only when it exited the runway. The supervisor took a mental note to revise his heuristic that seemed to work in previous situations. Throughout the approach, the controllers reported that they had a feeling that something was not going well, despite conformation from the flight crew that they could see the runway. The team supervisor felt that the report of the flight crew puzzled him instead of easing him.

7.5 Epilogue

A few minutes after landing, the flight captain made a telephone call and thanked the controllers for the cooperation and the professional vectoring to avoid weather. Because the lack of applicability of the rule regarding visibility was still in the mind of the team supervisor, he decided to ask the captain how he was able to see the runway at 1,200 ft. The captain reported something unexpected—when he said that he had the runway in sight at 1,200 ft he was not actually able to see the runway but, in his opinion, the clouds were diffusing and their base was near. He decided to descend lower, assuming that the ILS system was not really malfunctioning—although it was declared non-operational by the ATC units due to the construction work that took place. He saw the runway at about 180 ft, at the very last moment when he was seriously contemplating a go-around. In other words, the captain was pressing the approach, hence, sidestepping the TVOR procedure (see Fig. 4 for all relevant altitudes). The team supervisor said nothing to the captain, reported the full story to the Tower controller and realized that his earlier rule was still valid after all. During the CDMs both controllers reported that they remembered vividly the tone of voice and registered the captain words for the future in order to make any necessary comparisons, should they were face a similar case; they thought that they were rather misled in this particular scenario.

What this case study clearly illustrates is that the stopping rule for the sensemaking process was indeed 'enforced' upon the two controllers with no means of cross-checking it other than an unofficial discussion.

8 Discussion

The term macrocognition was coined by (Klein et al. 2003) to describe a class of cognitive functions performed in natural decision-making settings as opposed to laboratory environments. Macrocognition has evolved to encompass the adaptability of practitioners required in complex environments. The data/frame model of sensemaking has been one of the most important macrocognition functions and is subject to similar criticism regarding reliability, validity and scope of application. Such criticism, however, can be a healthy research issue as it provides compelling motivation to improve our research methods and fine tune their theoretical underpinnings.

From our study, it is possible to contemplate some limitations of the data/frame model. The data/frame model assumes that a stopping rule exits when the sensemaking process terminates; it concerns the moment when data and frames are brought into congruence (Klein et al. 2007). This presupposes that the practitioner knows in advance that there is no other informative data to account for, or that the data is not likely to change the frame in an important way. The data/frame model also assumes that the stopping

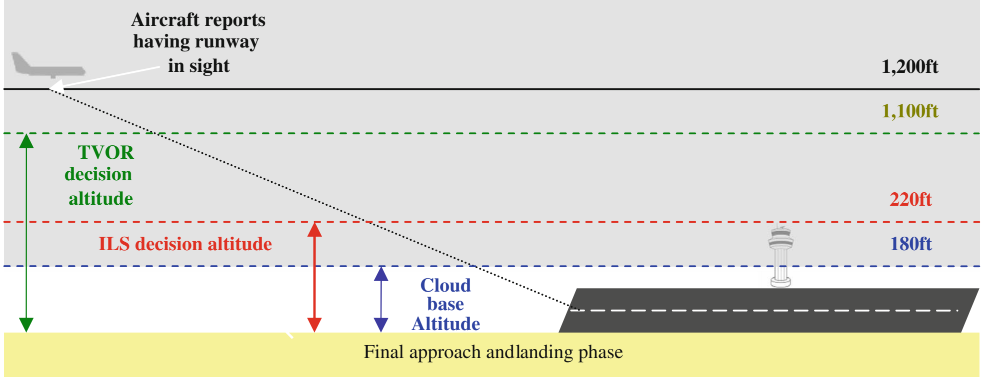

Fig. 4 A graphic of the *vertical* profile of the aircraft in its final approach (not in scale)

rule is not forced by the work environment without any means of cross-checking. In fact, Cohen (2011) has argued that the stopping rule itself determines the frame and not vice versa; experts are likely to continue their search for more data in real settings as the cost of errors may outweigh the cost of delays.

The case study in Sect. 7 illustrates that the stopping rule was indeed 'enforced' upon the practitioners with no means of cross-checking it. In the ATM environment, it is highly unprofessional to question the validity of reports made by flight crews although suspicions may cripple in some events. In most cases, the operational concept of LVOs guarantees that the stopping rule (i.e., the finding of the precise altitude band of the cloud base) is tested and validated on every approach for landing. However, the stopping rule may be imposed upon controllers with no means of cross-checking, hence resulting in wrong inferences. Had it not been the final feedback by the flight crew, the controllers would have no idea what really happened and they would have probably revised their network of *if–then* rules falsely based on wrong explanations. Pressing on with the approach in LVOs and informing accordingly the ATC is not uncommon. A recent accident illustrated a similar pattern when the Polish presidential aircraft crashed during its approach at Smolensk Severny aerodrome. In low visibility conditions, the flight crew descended having passed the published minima of the airport, without informing the controllers (CINAA 2011). The aircraft had been diverted from its original destination and there was great pressure to land as it carried the Polish President as well as top ranking military and political officials.

Controllers have accumulated expertise in several areas that may be put at the risk of being utterly invalidated from the introduction of new ATM technologies. Specifically, controllers have developed networks of *if–then* rules regarding visibility that are used as a resource in constructing their frames. With the introduction of satellite navigation systems that allow lower minima and provide synthetic vision, controller competence may be invalidated. The base of clouds would no more be a determining factor for a successful landing, or a go-around procedure, and hence, relevant expertise may be lost.

Another example concerns key information for developing frames to manage heavy traffic. New ATM systems introduce shared separation roles between pilots and controllers which may reduce the number of predictable 'hot spots' and conflict points within a sector; as a result, the controller level of effort to make sense of potential conflicts will heavily increase. In the current system, potential conflicts would be located close to known waypoints. In the new system, conflicts and hot spots could appear virtually at any point in the airspace since controllers would not be able to know in advance how information technology may change routes and perform 'traffic synchronization'.

Controllers have spent considerable time learning their airspace, and they have developed certain expectations of traffic that flows through their sectors. One aspect of the learning process involves understanding the peculiarities of the airspace—controllers learn to recognize subtle cues in a stable environment that give them an almost intuitive feel for an answer to a particular problem. However, in a flexible routing context advocated by new ATM systems, such predictable patterns may no longer exist.

Sensemaking also becomes an issue when the flight deck and air traffic control both have similar, but not necessarily identical, information available. An example already exists for aircraft that carry onboard radar to detect weather ahead of them. The information that controllers have on their displays is not as fine-grained as the information that these pilots have available. When controllers and pilots communicate about weather, they do not have a shared awareness of the situation. In a similar fashion, Traffic Information Service Broadcast (TISB) systems will provide pilots with information that may not correspond with the information controllers have available. In a flight path diversion due to weather, for instance, controllers will not have the same quality information about weather that pilots would be provided with and, hence, they could not anticipate when pilots may require to rejoin their original flight path. This brings forward another critical issue with regard to flight crew decisions when encountering a malfunction and requesting assistance from controllers who have been 'out-of-the-loop' for long time periods. Diminishing relevant controller expertise would put at risk any sudden intervention of controllers when requested by crews failing to control a critical situation.

The vision of future ATM systems is based on the concept of flight trajectories approved—through collaborative decision making—by airspace users, ATC providers and airports. However, it is still an open question how this distributed decision making can achieve optimal outcomes for all stakeholders. Research into team sensemaking can provide useful insights on how to embed operational experience into future ATM systems in order to improve collaborative decision making at a large scale. There is also a need for developing appropriate forms of decision support systems that would enhance sensemaking skills especially in view of the data overload problem that may be created by new developments in the SESAR and NextGen programmes.

References

Bearman C, Paletz SBF, Orasanu J, Thomas MJW (2010) The breakdown of coordinated decision making in distributed systems. Hum Factors 52:173–188

Burke CS, Stagl KC, Salas E, Pierce L, Kendall D (2006) Understanding team adaptation: a conceptual analysis and model. J Appl Psychol 91:1189–1207

Cardosi KM (1993) Time required for transmission of time critical air traffic control messages in an en route environment. Int J Aviat Psychol 3:303–314

Committee for Investigation of National Aviation Accidents (CINAA 2011). Final report from the examination of the aviation accident no 192/2010/11 involving a Tu-154M airplane which occurred on April 2010 in the area of the SMOLENSK NORTH airfield. http://mswia.datacenter-poland.pl/FinalReportTu-154M.pdf

Crandall B, Klein GA, Hoffman RR (2006) Working minds: a practitioner's guide to cognitive task analysis. MIT Press Massachusetts Institute of Technology, Cambridge MA

De Keyser V, Woods DD (1990) Fixation errors: failures to revise situation assessment in dynamic and risky systems. In: Colombo AG, Saiz de Bustamante A (eds). Systems Reliability Assessment, pp 231–251

Endsley MR, Smolensky M (1998) Situation awareness in air traffic control: the picture. In: Smolensky M, Stein E (eds) Human factors in air traffic control. Academic Press, New York, pp 115–154

Federal Aviation Administration (FAA) (2010) FAA's NextGen implementation plan, March 2010, Federal Aviation administration

Federal Aviation Administration (FAA) (2012) FAA's NextGen implementation plan, March 2012, Federal aviation administration

Hansman RJ, Davison HJ (2000) The effect of shared information on pilot/controller and controller/controller interactions. Third USA/Europe Air Traffic Manage-ment R&D Seminar, Napoli

Hoffman RR, Crandal B, Shadbolt N (1998) Use of the critical decision method to elicit expert knowledge: a case study in the methodology of cognitive task analysis. Hum Factors 40: 254–276

Hoffman RR, Trafton G, Roebber P (2006) Minding the weather: how expert forecasters think. MIT Press, Cambridge MA

Hollnagel E (2007) Flight decks and free flight: where are the system boundaries? Appl Ergonomics 38:409–416

International Civil Aviation Organization (ICAO) (2005) Global air traffic management operational concept, Document 9854 AN/458, 1st eds. International civil aviation organization

International Civil Aviation Organization (ICAO) (2006) Aircraft Operations, Document 8168 ATM/501, Fifth Edition. International Civil Aviation Organization

International Civil Aviation Organization (ICAO) (2007) Air traffic management. Procedures for air navigation services, Document 4444 ATM/501, 15th ed. International civil aviation organization

Kirwan B, Flynn M (2002) Towards a controller-based conflict resolution tool: a literature review (European Air Traffic Management Programme Rep. No.ASA.01.CORA.2.DEL04-A.LIT). EUROCONTROL, Brussels, Belgium

Klein G (1998) Sources of power: how people make decisions. MIT Press, Cambridge

Klein GA (2004) The Power of Intuition. A Currency Book/Doubleday, New York

Klein G, Ross K, Moon B, Klein G, Hoffman R, Hollnagel E (2003) Macrocognition. IEEE Intell Syst 18:81–85

Klein G, Moon B, Hoffman RR (2006a) Making sense of sensemaking 1: alternative perspectives. IEEE Intell Syst 21(4):70–73

Klein G, Moon B, Hoffman RR (2006b) Making sense of sensemaking 2: a macrocognitive model. IEEE Intell Syst 21(5):88–92

Klein G, Philips JK, Rall EL, Peluso DA (2007) A data/frame theory of sensemaking. In: Hoffman RR (ed) Expertise out of context: proceedings of the 6th international conference on naturalistic decision making. Erlbaum, Mahwah

Klein G, Wiggins S, Dominguez CO (2010) Team sensemaking. Theor Issues Ergonomics Sci 11:304–320

Kontogiannis T (2010) Adapting plans in progress in distributed supervisory work: aspects of complexity, coupling, and control. Cogn Technol Work 12:103–118

Kontogiannis T, Malakis S (2009) A proactive approach to human error detection and identification in the aviation and air traffic control. Saf Sci 47:693–706

Langan-Fox J, Sankey MJ, Canty JM (2009) Human factors measurement for future air traffic control systems. Hum Factors 51:595–637

Malakis S, Kontogiannis T (2012) A sensemaking perspective on framing the mental picture of air traffic controllers. Appl Ergonomics 44:327–339

Malakis S, Kontogiannis T, Kirwan B (2010) Managing emergencies and abnormal situations in air traffic control (Part II): teamwork strategies. Appl Ergonomics 41:628–635

Minsky M (1975) A framework for representing knowledge. In: Winston P (ed) The psychology of computer vision. McGraw Hill, New York, pp 211–277

Mogford RH (1997) Mental models and situation awareness in air traffic control. Int J Aviat Psychol 7:331–341

Morrow DG, Lee AT, Rodvold M (1993) Analysis of problems in routine controller-pilot communication. Int J Aviat Psychol 3:285–302

Patterson ES, Watts-Perotti J, Woods DD (1999) Voice loops as coordination aids in space shuttle mission control. Comput Support Cooperative Work: J Collaborative Comput 8:353–371

Piaget JKE (1954) The construction of reality in the child. Basic Books, New York

SESAR Joint Undertaking (SESAR-JU) (2012) European ATM Master Plan, 2 eds. October 2012, SESAR Joint Undertaking

SESAR Joint Undertaking (SESAR-JU) (2009). European air traffic management master plan, 1st eds. 30th March 2009, SESAR joint undertaking

Shorrock ST, Kirwan B (2002) Development and application of a human error identification tool for air traffic control. Appl Ergonomics 33:319–336

Sieck WR, Klein G, Peluso DA, Smith JL, Harris-Thompson D (2004) FOCUS: A model of sensemaking. Fairborn, Klein Associates

Weick KE (1995) Sensemaking in organizations. Thousand Oaks, CA

Weick KE (2007) Making sense of the organizations. Blackwell Publishing, MA

Woods DD, Patterson ES, Roth EM (2002) Can we ever escape from data overload? A cognitive systems diagnosis. Cognit, Technol Work 4:22–36