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Evaluation of ATC working practice from a safety and human factor perpective

(Application to the SESAR Concept of Operations)

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***Abstract*— In this paper we consider the implications of the SESAR Concept of operations on the working practice of ATC. After introducing the expected changes in the ATC working practice, and the necessity for the regulatory authority to address them, we survey the available approaches. Then, we introduce a methodology, based on existing material, which combines safety and human factor expertise in order to allow a high level assessment of ATC performance.**

Keywords: ATM performance, controller workload, quantitative safety assessment

I. INTRODUCTION

A. *Impact of SESAR on the ATC working practice*

Within Europe, the SESAR Concept of Operations (ConOps) introduces significant changes in the Air Traffic Controller (ATCO) working practice. Over the last decades, ATCO workload was perceived as the main constraint, and evolutions in Air Traffic Management (ATM) were performed in order to relax this constraint as much as possible. For instance, aircraft routes were designed in order to minimize the number of conflicts, sectors were designed in order to include routes as much as possible, and, in the case of traffic increase, the opening of a new Air Traffic Control (ATC) position was designed in order to reduce ATC coordination work as much as possible. In other world, the ATCO was at the center of the ATM world, and all other components were turning around him.

On the other hand, the SESAR ConOps is trajectory based, in the sense that aircraft trajectories are defined firstly, in order to minimize airlines costs (so that the aircraft optimal trajectory becomes the main constraint), and the ATCO activity results from it. In the new SESAR world, aircraft trajectories become the center of the world, and the other components (including ATCO) turn around it.

The SESAR ConOps makes an important use of the onboard position information provided by the avionics, and of its accuracy. Uncertainty of future aircraft trajectory will be reduced when 3D precision trajectory are implemented. From an ATCO perspective, the tasks of conflict diagnosis, which accounted for a significant amount of the ATCO cognitive workload, will no longer be necessary, since ATCO will have a reliable information on the future relative distance between pairs of aircraft, so that he will only focus on aircraft pair which are expected to pass below or close to the separation. In addition, conflict resolutions will be negotiated with the pilot through 2/3/4D contracts, and it is likely that ATCO will be provided with additional automated tools for assisting him in defining these contracts. From the perspective of airspace occupation, the 3D precision trajectory concept will result in a smaller containment volume (which is the tube/cone where aircraft are nearly sure to remain), so that conflict free trajectories will be possible with aircraft passing at a smaller relative distance than they currently do. In addition, conflict resolution will deviate less aircraft (heading changes being replaced by 4D contracts), so that conflict resolutions will keep aircraft at a closer relative distance.

Although the SESAR ConOps is ultimately directed towards self separation between aircraft without ATCO issuing conflict resolution, in the intermediate phase ATCO will still be in charge of maintaining adequate separation between aircraft. During this phase, the change from an ATCO-centric paradigm towards a trajectory-centric one raises several issues from a regulatory viewpoint. In the past the ATM has always evolved in a way which made the ATCO work both intuitive and immediate, at the cost of sub-optimality. Regulations mainly applied on technical components of the system, since the existing world had been curtailed according to the human performance. In addition, technological improvements did not modify significantly the ATCO activity; for instance, the increased accuracy of radar performance allowed reducing separations up to a certain extent, the reduction in separation corresponding to the better radar accuracy, but there was still a buffer to account for atypical events. In a similar way, the introduction of ADS-B in a procedural environment allowed to reduce separations, but again up to a certain limit.

For all the previous examples, the pre implementation safety cases would address the mitigation of technical failure, and the safety monitoring (post implementation) mostly relied on checking that the frequency of proximate events (which were the main “indicators” of the residual risk in the system) was not unacceptably high. In practice, the causality between proximate events and the risk of collision was considered to be strong enough for guaranteeing that, if the rate of proximate event was sufficiently low, the risk of collision would also be sufficiently low.

SESAR will require to identify a new category of hazardous events, which will have to be addressed both in the pre-implementation (through mitigation measures meeting safety objectives) and in the post-implementation phase (incident reporting and monitoring). Presumably, proximate events will no longer be the sole key indicators, since mismatches (in the general sense) between ATCO and its environment (failure or inappropriate application of an assisting tool, for instance) may become the main contribution to risk. This raises several issues: will it be possible to detect the new hazardous events? How can we objectively assess their severity and mitigate them? These questions are developed in the sequel of the paper. In the next subsection, we firstly review some background material, both for safety assessment of human performance in ATM, and for previous attempts to model ATCO performance for engineering purposes. Then, we introduce our approach, in the context of this background material.

B. Background

A well established methodology for addressing safety issues related to human performance is the Traffic Organization and Perturbation AnalyZer (TOPAZ) toolset, based on a functional representation of ATM, where the functional subsystems interact, allowing for mechanisms of error propagation. TOPAZ has been used for a wide range of applications, including simultaneous converging instrument approaches ([1]) and runway incursions based on different modeling of human performance ([5] and [6]). It would certainly be possible to make use of the sophisticated modeling of ATM made in TOPAZ for getting some insight on the limits of human performance, but TOPAZ is, as far as we know, mostly oriented towards the numerical evaluation of a risk, expressed into the metrics of “number of collision per system hour”. In the case of ATC, we need to express the limits of human performance in a more refined manner, whether they apply to the sensorial (audio and visual information sent to the ATCO), the heuristic (conflict solving tasks) or the emotional (stress, pressure) aspects.

Reference [7] recommends to use a *success and failure approach* when considering a new operational concept for ATM, where the success approach consists in evaluating the risk reduction brought by this new concept when properly working, by opposition to the failure approach which deals with the risk caused by an inappropriate or defective application of this new concept. Using the layered description of conflict management provided by the ICAO Doc 9854 [10], the success side becomes the reduction of the number of conflicts due to the strategic and all pre-tactic conflict management operations, whereas the failure side addresses failures at the tactical layer. Using this terminology, the regulatory authority must verify that the success approaches overwhelms the failure approach.

Reference [9] introduces a description of the operational risk based on *encounters*, which are aircraft pairs likely to fall into a predefined scenario of operational error. The operational errors considered in [9] are the situations where the aircraft behaves differently from what the ATCO had anticipated. For these encounters, the severity of the risk depends on the geometry of the encounter, and on the time available for ATCO intervention. In practice, these encounters are extracted from traffic data files, by a software processing. Figure 1 illustrates such an encounter, where the associated scenario of operational error is a non execution of the ATCO instruction by a descending aircraft instructed to level off.

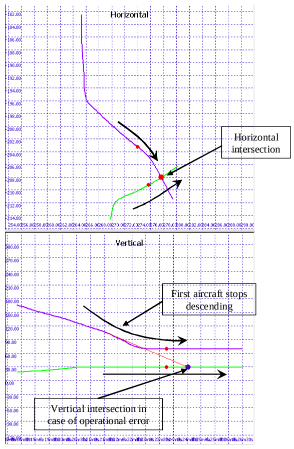

Figure 1: example of encounter (drawn from [9])

In practice, these encounters are firstly validated, in the sense that an operational expert manually checks (by playing the encounter with an appropriate software editor) the soundness of the associated scenario of operational error. In a second time, each encounter contributes to the total risk, and the risk of collision (under its scenario of operational error) is determined by making use of a 3D collision risk model. In this paper, in order to analyze the evolution of ATCO working practice, we have followed an approach similar to [9], in the sense that we still make use of *aircraft encounters* in order to describe the different facets of ATCO work. These encounters still represent aircraft pairs with an associated scenario of traffic evolution, but they are now used in order to describe both the cognitive and the risk related aspects of ATCO working practice, so that our approach is at a higher level than in [9]. Our general intent is to evaluate the change, for the ATCO working practice, resulting from an evolution of the ATM, in the general sense (introduction of a new tool, change of procedure, new concept of operation, and so on). We are mostly interested into verifying if this evolution is within the bounds of the human performance of ATCO. Our approach proceeds in two steps; in the first step, we show how to define the encounters which will be appropriate for analyzing the variation in the ATCO working practice. Then, in the second step, we show how these encounters can be processed in order to describe both risk and workload.

When considering ATCO workload, we have made an implicit use of the general description of the ATCO activity made in [8], that we very briefly summarize. ATCO activity is characterized by a processing of massive information, which is time dependent with regards to its availability and accuracy. In addition, this activity is cooperative, and aims at producing real time decisions under different kinds of pressure (pressure in time, risk, team pressure). The model presented in [8] is inspired from cognitive engineering, and the author highlights that his model is only valid within a certain domain of application. For abnormal situations (the highest cognitive demands, for instance), other mental modes are likely to occur.

As a general rule, in this paper, we have preferred to introduce ideas in an intuitive rather than academic approach. When discussing technical issues (collision risk modeling, ATCO cognitive model), we remain at a reasonably high level. The reason is that the scope of this paper addresses three different but complementary areas, as the three authors' background illustrate:

- Qualitative and quantitative modeling of risk
- ATC workload and human performance
- Regulatory aspects of the two previous areas

This being said, we have provided sufficient references for satisfying the curiosity of the interested reader. In the next section, we introduce a systemic approach for defining encounters with regards to safety and ATCO cognitive workload. Then, in the next section, we show how to process these encounters, both quantitatively and qualitatively. Finally, we illustrate our approach with an application made in the context of the ERASMUS project.

II. High level description of ATM from an ATC perspective

The definition of the encounters results from a high level description of ATM from an ATC perspective. Within ATM, the air traffic controller receives and sends information according to various predefined patterns, and he also processes the received information in an expert way. By describing these two aspects (information exchange and information processing), it becomes possible to determine an exhaustive set of scenarios of operational errors, as we now explain.

A. *Description of ATM in terms of "information loops"*

In this section we firstly introduce a general description of the ATC practice from a cognitive perspective. Our description relies on the multi-distributed nature of ATM, where the agents exchange information according to well defined patterns:

- Pilot → ATCO: information related to the flight (when entering a sector), or acknowledgment of clearance.
- ATCO → Pilot: In the current ATM, clearance to modify the trajectory (in case of conflict), or to transfer to next sector. In the future, airborne separation will lead to delegation of separation from ATCO to pilot
- ATCO → ATCO: coordination within adjacent sectors when a conflict resolution modifies the trajectory not only in the current sector, but also in the next one.
- Pilot → Pilot: in the current ATM, only used for situational awareness (on CDTI), or in the case of collision avoidance managed by TCAS. In the future, the introduction of self separation will lead to information exchanges between pilots.

In the real world, these elementary patterns are usually combined into loops, as the following examples illustrate:

- The ATCO instructs a pilot to modify its frequency and contact the next sector: ATCO → Pilot → ATCO.
- The ATCO applies a conflict avoidance instruction, and informs the ATCO in the adjacent sector of the route modification: the information follows both ATCO → Pilot and ATCO → ATCO.

In addition to the exchanges of information between the different agents, ATCO is continuously fueled with a mass of surveillance information (aircraft positions in a radar environment), plus extra information for alarming (STCA, MSAW) or helping to solve tasks (display of future separation losses, display of clusters of conflicting aircraft).

For each information sent between a sender and a receiver, the loss of information is likely to cause a hazardous situation. This loss has to be understood in the most general way, as the following examples illustrate. A first scenario of loss of information occurs when some information is not received by an agent, such as a pilot not executing a clearance whereas he was instructed to do so, or a pilot failing to transfer to the next sector whereas he was instructed to do so. This loss of information may result from a wide range of possible errors (phraseology, confusion on the callsign), but this is outside of our current scope. An agent may also receive at the same time two information of contradicting nature, like the Uberlingen accident, where the pilot was instructed by ATCO and by TCAS in two different ways, so that the crucial information (TCAS RA) was lost. Similarly, when two ATCO A and B from adjacent sectors coordinate, a misunderstanding may occur, if for instance A designates an aircraft and B confuses it with another one. Finally, an agent may also misread an information, for a wide range of reasons: for instance in TMA, if the ATCO is used to see everyday the same flight entering the sector at the same FL, and if one day this flight enters at a different FL, the ATCO is likely to be confused, although the information is properly displayed on its scope.

In summary, scenarios of loss of information represents all situations where important and correct information was sent but where the receiver of that information did not integrate it in its cognitive representation of the world. During the safety assessment, these scenarios need to be addressed, both in the pre-implementation and in the post-implementation phase. Particular care has to be exerted on the post-implementation phase, and on the monitoring of these events.

Scenarios of loss of information by the pilot in the case of ATCO clearances have already been considered in [9], but only for safety purpose. These scenarios also impact on the cognitive workload of the ATCO, since the ATCO, when giving a clearance, actually keeps on watching an aircraft on its scope, in order to check that the information has been properly processed. This gives one example of description of ATCO workload in terms of encounters.

In the next section, we develop in further details the processing of information by ATCO, and its consequences on safety and on cognitive workload.

B. Processing of information by ATCO

The processing of information by ATCO is a complex issue, and we have already presented ([8]) an attempt to describe it. In order to illustrate the kind of scenarios of operational error which stem from this processing, we have proceeded by analogy with the game of chess. This has led us to restrict our scope for the ATCO processing of information to the mere use of *logical memory* by ATCO, where logical memory accounts for the ability to store information in order to allow quick access upon "intelligent" requests. An illustrative example of logical memory is the mental visualization of an itinerary between two points (personal address and working place, for instance), with an additional constraint (rerouting due to an accident). Following that example, we notice that the itinerary does not need to be optimal (in terms of length or time): what is really important is to be able to design such an itinerary as quickly as possible, for instance in the case of a driver forced to change its route due to an accident.

In the case of ATCO, logical memory is used for getting an intuitive knowledge of the possible states which may result from a given state. Similarly, experienced chess players, when looking at a given chess position, can identify at once from which chess opening it is drawn, and which classical games have been played from that position.

It is important to understand that the use of logical memory both in the game of chess and in the ATCO working practice results from a *refined learning mechanism*: The ATCO, like the gifted young chess player, "stores" in his mind the position that he has already experienced, together with the possible outcomes, provided he has a competent master telling him how to prevent the repetition of the same mistake by pointing him out what was the "first bad move" not to be repeated in the future.

The use of logical memory has two consequences on the outcome of possible scenarios of errors, which we explain by still considering chess game. Firstly, a chess player which plays blindly can "forget" or "move" a figure, because the position without the figure is also a classical one. This scenario of error is similar to the one where an ATCO fails to identify that a flight arrives at a different flight level a particular day, because he has been used to see the flight arriving always at the same flight level in the past. The second scenario is more diffuse, and applies to the use of automated tools. Software for solving optimally (with the smallest possible number of moves) chess endings is currently available; however, top chess players do not solve chess endings optimally, they rather solve it by transferring to another position that they know to be winning: chess players play under a time constraint, and that very limitation causes top chess players to play more moves than required in order to win, but in a nearly intuitive way, very little time consuming. This relationship between conflict solving and time resources has also to be taken into account when considering automated conflict solver. In the same line, we reproduce an extract from [8], written by Marcel Leroux, main designer of the French ElectRonic Assistant for en-route air Traffic contrOllers (ERATO) [8]:

> *The man-machine interaction must meet the following conditions, cited according to their criticality:*
>
> - ***enable operators to exercise all the mental mechanisms that enable them to build the relevant mental representation of the system to be monitored****,*
> - *enable operators to cooperate in an efficient way,*
> - *enable efficient inputs into the system.*
>
> *These three points are necessary, but too often the third is the tree that hides the forest, while its single purpose is to ease the first two.*

In the section devoted to the application to ERASMUS, we will present an attempt to describe the ATCO mental representation of traffic, when dealing with conflict solving.

After addressing the safety issues related to SESAR, we now address the operational benefits, from an ATC perspective. In the next subsection, we introduce a modeling for assessing the cognitive workload in the current ATM environment, considering that a significant part of this workload will be freed when SESAR will be implemented.

C. ATCO current perception of cognitive workload

ATCO uncertainty on future 4D positions significantly hinders conflict anticipation ([1]). For the ATCO, this uncertainty results in a double doubt: is a conflict resolution necessary? If so, what trajectory modification is suitable? These two levels of doubt significantly contribute to ATCO workload, to such an extent that the management of this doubt has been identified as an essential component of ATCO expertise ([3]). When considering ATCO cognitive workload, a fundamental point is that the resolution of the ambiguity conflicting/not conflicting has more significance than the task of conflict solving. Conflict resolution has limited choice (horizontal/vertical speed, flight level, heading), but always sufficient provided it is timely applied. What is costly in terms of cognitive resources is to determine the necessity for acting, and the optimal action. This idea is captured in the following quotation, extracted from [8]:

> *Controllers spend a large amount of time in ambiguity elimination processes. Allowing a doubt is a luxury for the controller;* ***the mastery of doubt is an art****.*

Reference [1] introduces an index of mental workload which accounts for the cognitive resources involved in the process of ambiguity resolution. The purpose of this index is to **model a trade off between uncertainty and time pressure**, based on the concept of *maturing time*. The maturing time is the time elapsed between the conflict diagnosis and the time when resolution is undertaken. The conflict diagnosis is said to be set down once the controller has enough doubt about the future separation between the two aircraft. The time interval between this moment and the resolution implementation stems from necessary tradeoff between two contradictory interests: reducing uncertainty – while getting closer to the exact separation values – and minimizing the mobilized resources. Indeed, the longer the controller waits for issuing a resolution, the less coercive/ the more necessary the resolution will be for the aircraft. But on the other hand, he will have to pay longer attention to the situation, consequently mobilizing additional cognitive resources. Conversely, an early resolution (at the time of the diagnosis) will entail the lowest cost in terms of controller workload, but also induce a larger (or even unnecessary) trajectory deviation. The more costly situation, for the controller, is – paradoxically – when he does not issue any resolution, so that he keeps on watching the aircraft pair until he has enough certainty that the separation will not be infringed. That is also the reason why the resolution implementation times can be viewed as a means of workload self-regulation.

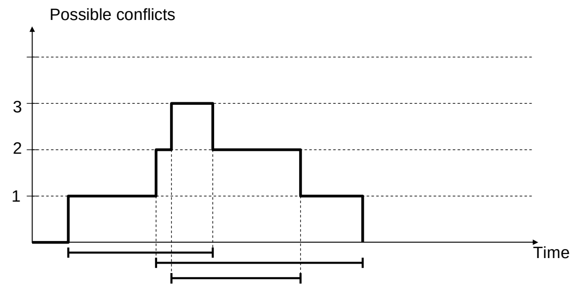

Figure 2: maturing time for different conflict resolutions associated to different aircraft pairs

If we represent (Figure 2), for each possible conflict, the maturing time as a time interval (between the time of diagnosis and either the ending time or the resolution time if a resolution occurred), we can get an insight of the ATCO cognitive workload, expressed in terms of aircraft possible conflicting pairs. An application of this cognitive workload for measuring the benefits of SESAR 3D precision trajectories is illustrated in Figure 3, reproduced from [13]. In the current ATM, the ATCO would issue two conflict resolutions for the two intruding aircraft of the top case of Figure 3, whereas the introduction of 3D precision trajectories is expected to remove these two resolutions.

In addition to reducing the number of conflicting aircraft pairs, 3D precision trajectories could contribute to reducing ATCO cognitive workload in several ways, that we no survey. Firstly, if the accuracy of 3D precision trajectories was high enough for allowing accurate estimation of separation between aircraft pairs with a large anticipation time (significantly larger than the duration for an aircraft to cross an ACC), then, it could be possible to design an automated conflict solver, which would, by advance, solve conflicts with a minor effect on aircraft trajectories.

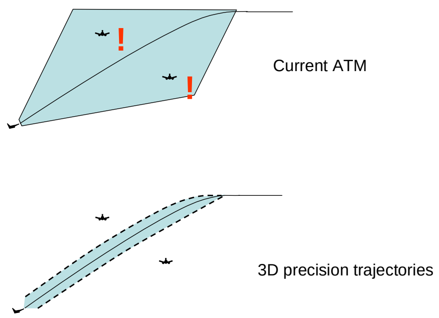

Figure 3: reduction of possible conflicts due to 3D precision trajectories (reproduced from [13])

This concept is the cornerstone of the ERASMUS project, and we will develop more in detail in the sequel of this paper. A second benefit which could be drawn from 3D precision trajectory is to provide ATCO with the information of future separations for aircraft pairs, so that he would know without any ambiguity which aircraft pairs will be conflicting in the future. If this was the case, the cognitive resources involved during the maturing time would no longer be required, and could be used for other purposes.

In this section we have surveyed the operational benefits of SESAR ConOps, together with the new safety issues to be considered, and we have presented, for both aspects, a modeling based on the definition of appropriate encounters. For the operational benefits, encounters should be defined in order to describe cognitive workload for ATCO, and for safety issues, encounters should capture all possible scenarios of operational errors likely to occur. Since the SESAR ConOps heavily relies on the use of onboard information, this is the aspect that we have mostly covered when considering scenarios of operational errors.

Once the encounters have been defined, the principle is to run experimentations, where air traffic controllers are presented baseline scenarios (in their current ATM environment), together with scenarios where the new ATM environment is implemented. For each case, encounters are extracted by automated software processing. In the next section, we now cover the processing of encounters, once they have been defined and extracted. Once again, this processing is intended to provide insight on both the safety and the ATCO workload aspects. Safety aspects are addressed, once more, by using collision risk models, whereas ATCO workload aspects are addressed in a more qualitative manner, as we now explain.

III. EVALUATION OF THE ENCOUNTERS IN AN ATCO PERSPECTIVE

Encounters can be evaluated either in a quantitative or a qualitative manner. We develop these two aspects in the two following subsections.

A. Quantitative evaluation of encounters

In this paper we restrict ourselves to the quantitative evaluation for safety purpose. We have already presented in [9] a 3D Collision Risk Model (CRM) designed in order to associate to each encounter a probability of collision. A recently published ICAO circular ([12]) provides a unified framework for designing collision risk models according to any modeling of the uncertainties, so that it is now possible to design CRM in a more rigorous manner, as we now explain. Within ICAO material, CRM are mainly used for quantitative safety assessment of airspace planning, in [11]. The main benefit of [12] is that it provides a unified derivation of all the CRM presented in [11], which appear to follow from the same generic equation, so that the differences between the various CRM are due to different modeling of uncertainties.

How can we model uncertainties without losing the consistency with ATCO working practice? Let's consider for instance the encounter shown in Figure 4. This encounter is extracted from traffic, and the two aircraft trajectories are plotted with bullets, together with their flight plans in dashed. The ATCO has issued a conflict resolution by instructing the left aircraft to maintain its heading, and the right one to turn right. The scenario of error associated to the encounter is the one where the right aircraft does not perform the turn, but keeps on in straight line. How should we model the uncertainties associated to this scenario, in order to remain consistent with the reality? The two aircraft trajectories are fixed in the sense that they are constrained by their flight plan and by the past of the flight, so it does not make any sense to model the operational risk of collision by adding positional uncertainties to the aircraft. Actually, positional uncertainties would model the surveillance inaccuracy, but since the two aircraft have been flying in straight line for a consistent time before the ATCO issues the instruction, the ATCO has "corrected in his mind", and the only surveillance error that he could not have corrected would be constant errors (such as bias), but under radar surveillance these errors apply to both aircraft and do not have any effect on their relative position error. Instead of modeling the uncertainties by position error, it makes more sense to assume that the two trajectories are deterministic, but that the only source of uncertainty, in horizontal, would have been a time offset of one aircraft relative to the other, so that one aircraft could have arrived slightly earlier or later. Moreover, the range of this time offset can be determined by noticing that the ATCO issued its resolution because he had diagnosed a possible loss of separation in the future, so that the aircraft would have passed below, say, 10Nm, if the right aircraft had not been instructed to turn. By doing so, it becomes possible to determine a time window, for the time offset, which would still keep the aircraft in a "possible separation loss in the future". Finally, once the upper and lower bounds for the time offset are determined, we notice that the time offset has no reason to have one particular value rather than another, so that the time offset should be uniformly distributed within the two lower and upper bounds previously determined.

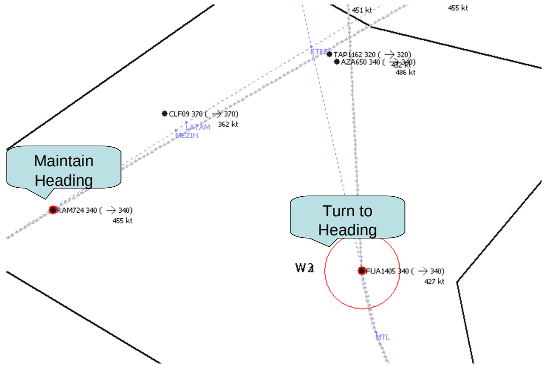

Figure 4: Example of conflict resolution encounter

The point that we want to make is that the modeling of uncertainties implicitly defines the nature of the risk that we describe. If we wish to evaluate the safety gain linked to the introduction of 3D precision trajectories, a first look at Figure 3 would suggest us to associate to aircraft position a positional error distributed according to the radius of the tube. This is not incorrect, but the risk that we describe by doing so is the **technical risk**, due to a failure of the avionics performance. If we want to model scenarios of loss of information similar to those described in subsection II.A, **the introduction of time offset errors,** similar to the previous example, seems more adapted. Furthermore, from a regulatory viewpoint, if the objective of the collision risk model is to design performance requirements on the accuracy of the 3D precision trajectories, then **the performance requirements should apply on consecutive errors for an individual aircraft**. What we mean is that an isolated position error on one individual aircraft would be easily detected by ATCO, so that it does not convey any risk. The ATCO might not detect a large position error only if one individual aircraft exhibits consecutive and constant positional errors. Our last comment only applies, of course, to environment where the surveillance would rely solely on position information sent by the avionics (in ADS-B, for instance or, to a lesser extent with altitude mode-C reporting).

We conclude this subsection by pointing out again the most important point: the unified framework for designing collision risk models [12] allows to model a risk of collision for any modeling of uncertainties, but the underlying of uncertainties needs to be clearly explained, together with the nature of the associated risk (technical or operational).

We know consider the processing of encounters in a qualitative way.

B. Qualitative evaluation of encounters: illustration with the ERASMUS project

The qualitative evaluation of encounters consists in the processing of encounters in order to get insight on qualitative aspects of the ATCO working practice. In this subsection, we introduce some results which were obtained in the context of the safety assessment study made in the En Route Air Traffic Soft Management Ultimate System (ERASMUS) project. We recall that the ERASMUS projects explores ways to reduce ATCO workload by issuing minor ("subliminal") speed modifications to the aircraft which are found to either further violate the separation minima or to be too close to them (up to 15 Nm, for instance). As we said previously, such aircraft pairs are accountable for the major of ATCO mental workload, as long as no conflict resolution is issued (maturing time). The speed changes mentioned above have a sufficiently low magnitude for ATCO not to notice them, but can be exerted long enough (up to 15 minutes) to significantly increase the initial separations in order to transmute conflict and doubtful diagnosis (costly in terms of cognitive resources) into non conflict ones (less resources demanding). The SESAR project should take up this concept again (renamed TC-SA).

In the framework of the ERASMUS project, DSNA has conducted several experimentations (Real Time Simulations) involving air traffic controllers of the Aix-Marseilles ACC, in order to assess the operational benefits of ERASMUS and ATCO workload variations. In one of these experimentations, the methodology introduced in this paper has been used, and the results can be found in the deliverable [14]. In this experimentation, eight traffic scenarios were designed using recorded real traffic from Aix-Marseilles ACC. Each of these scenarios was further subdivided into two subcases: either the controllers managed the traffic **together with** (but not knowing it) the ERASMUS solving algorithm, or **without** it i.e., exactly the situation they currently have. These two subcases were also automatically run, without any controller in the loop. The interests of the latter were respectively to assess the effect of the solving algorithm alone, and to quantify the conflicts that nominally existed in the scenario (without any automatic or human intervention).

When running the traffic scenario, the subliminal speed instructions were given by the solver to aircraft subject to a conflict risk (encounters) before they entered in the sector. The encounters extracted from the simulation traffic files corresponded to all proximate events, a proximate event being defined as an aircraft pair separated by less than 12 Nm in horizontal without being vertically separated. Afterwards, when processing the experimental data, an additional distinction was made, whether an instruction had been issued or not by the ATCO. Moreover, when issuing the instruction, the ATCO possibly did not intend to solve a conflict; possible other causes include, for instance, comfort considerations, or compliance with procedures. Nevertheless, all retained encounters corresponded to situations where, if the ATCO instruction had not been followed, the aircraft pair would have passed "reasonably close" to the separation. For all the retained encounters, the scenario "without ATCO resolution" was also determined, and the **horizontal minimal distance without being vertically separated** was determined, in the case where the resolving instruction had not been followed.

Figure 5 and Figure 6 show, for each encounter where the ATCO issued a resolution, the minimal horizontal distance without being vertically separated, if the ATCO instruction had not been followed. Horizontal and vertical encounters correspond to encounters where the ATCO resolution took place in horizontal or in vertical. Looking at Figure 5, we see that the *actually conflicting pairs of aircraft* (which are those which would have passed below 5Nm without being vertically separated) sum up to 1+3+9+13+7=33 without activating the ERASMUS solver, and to 2+1+1=4 with the ERASMUS solver "ON", which is an 87% reduction.

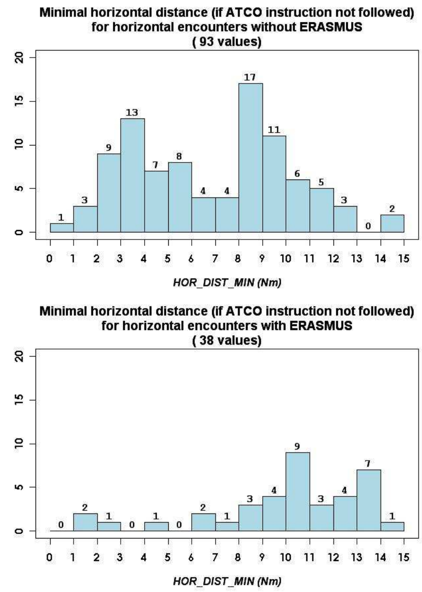

Figure 5: ATCO workload reduction in horizontal with ERASMUS

Similarly, in Figure 6, ERASMUS reduces the number of *actually conflicting pairs of aircraft* from 7+6+3+2+4=22 to 1+3+5=9, which is a 59% reduction. So, the overall benefit of ERASMUS, when considering the overall number of *actually conflicting pairs of aircraft*, is a reduction from 33+22=55 to 4+9=13, which is a 73% reduction, where the benefits seem to be slightly better in horizontal than in vertical.

Moreover, it was interesting to assess the anticipation made by ATCO when issuing conflict resolutions. The anticipation time has been extracted from the set of encounters where a conflict resolution was issued by ATCO, as the difference between the time where the two aircraft would have been at their minimal horizontal distance without being vertically separated, and the time when the resolving action was issued by ATCO. It has to be noticed that this anticipation addresses the decisional output rather than the cognitive process as a whole. A more refined definition of anticipation, including the bounds of the maturing time previously introduced, would have been a sounder indicator, and this is part of a future work.

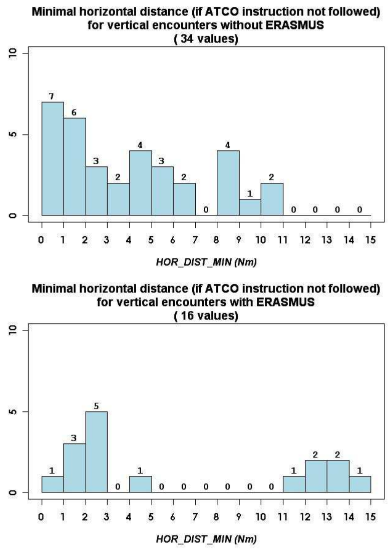

Figure 6: ATCO workload reduction in vertical with ERASMUS

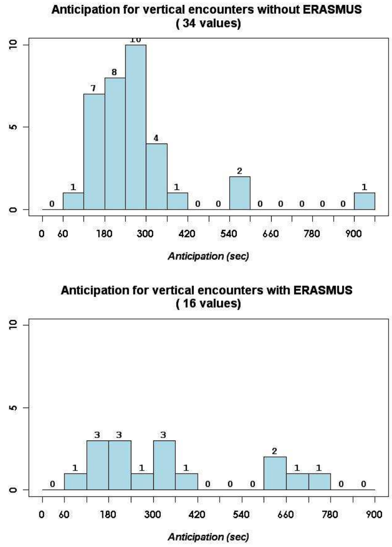

Figure 8: ATCO anticipation of vertical conflict resolutions without and with ERASMUS

Figure 7 and Figure 8 show the values for the anticipation, for horizontal and vertical encounters, with and without ERASMUS. We notice that without ERASMUS the anticipation has a wider variation for horizontal encounters than for vertical encounters. In other words, when ATCO issues a conflict resolution in vertical without ERASMUS, the anticipation is mostly contained in the interval of 2 to 5 minutes before the point of horizontal minimal distance.

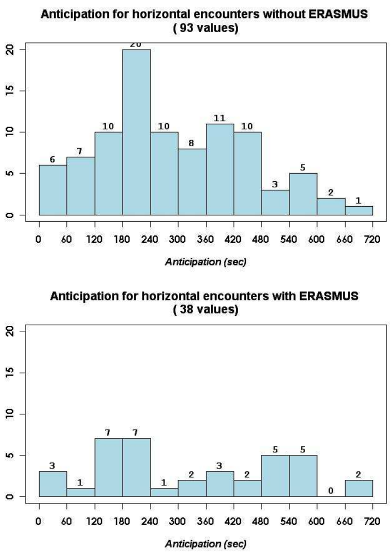

Figure 7: ATCO anticipation of horizontal conflict resolutions without and with ERASMUS

For horizontal conflict resolutions without ERASMUS, the anticipation is more spread, between 2 and 8 minutes before the point of minimal horizontal distance, with a small peak between 3 and 4 minutes. The introduction of ERASMUS significantly decreases the variation of anticipation for horizontal encounters, which are mostly in the two intervals [2 min, 4 min] and [8 min, 10 min] before the minimal horizontal distance. For vertical encounters, however, the effect of ERASMUS is less clear cut.

Finally, the joint display of the minimal horizontal distance without being vertically separated and of the anticipation reveals how ATCO schedule their work, as we now explain. Figure 9 and Figure 10 aggregate the four previous Figures, on a two dimensional representation. The main difference with the previous Figures is that the focus is now made on the ATCO instructions, rather than on the encounters, in the sense that when the same instruction applies to several encounters (only two, most of the time), then these encounters are linked by segments.

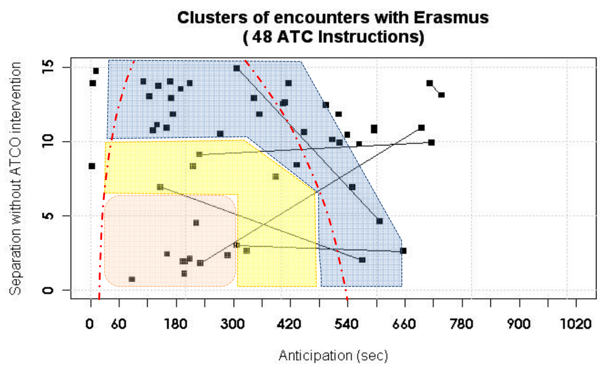

Figure 9: ATCO cognitive workload solicitation with ERASMUS

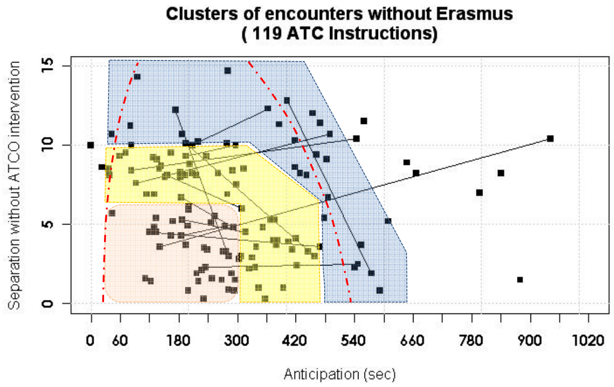

Figure 10: ATCO cognitive workload solicitation without ERASMUS

We now explain the classification made in Figure 9 and Figure 10. Firstly, ATCO actions having other objectives than conflict resolution have been empirically identified by the two red dashed lines. The rationale for these lines is twofold: for encounters on the left, the anticipation is too low for any separation provision purpose (either already sufficient from the controller's viewpoint within this phase, or too late to be created). To the right part of the dashed red lines are the very long term encounters (from controller's perception viewpoint). They cannot have the capacity of soliciting a conflict diagnosis from the ATCO since aircraft are still too far from their closest point of approach (CPA). This is easier to realize when knowing that the longest dimension of the sector considered here is about 70 Nm long, corresponding to an anticipation of 540 seconds, approximately. Therefore, the encounters which can be related to the actions implemented stand between the two dashed lines. The major part of controllers' mental load globally derives from the underlying cognitive processing of these encounters.

A further distinction was operated, according to the ATCO capability to perceive risk. It has to be noticed that this perceived risk – and by implication, its associated workload – may differ from the objective severity associated to the conflict (the future separation values at the CPA), as explained in [1]. Indeed, the **time span** between ATCO judgment and the CPA time greatly affects this perception, and consequently the cognitive processing and workload associated to it. For instance, rather than clearly appearing as conflicts to the controller, severe (potential) separation losses generate doubt in controllers' mind. This doubt progressively clears away when the two involved aircraft come close enough to their CPA (roughly between 20 and 40 Nm i.e., 4 to 5 minutes of flight time, mainly depending of the configuration geometry). This doubtful period is less resources demanding than when the conflict diagnosis is made – and the available time for acting is reduced. This leads to a partition of encounters in Figures 9 and 10 into three concentric "onion layers" when combining each time the severity and the time span defined above, for each encounter. They define:

- The highest level, shown in salmon, corresponds to encounters which would have passed below the separation if the ATC had not issued any instruction. The area in salmon covers approximately the most resources demanding encounters (mandatory interventions from controllers), as long as this intervention has not been done.
- An intermediate level, in yellow, based on either a "5 to 10 Nm separation at CAP" without ATCO intervention, or possibly less than 5Nm but with additional time span. These encounters represent the **ATCO area of doubt**. As we previously emphasized, encounters in that area are accompanied by a significant level of cognitive workload as long as a resolution is not implemented,.
- The third level, in blue, based on either a "separation higher than 10Nm at CAP" without ATC intervention, or less than 10Nm but with very comfortable time span, represents the **ATCO comfort area**, in the sense that, most of time, the controller exercises a significantly lower degree of attention for them. In other terms, these last resolutions correspond – during a certain period of time – to a moderate risk diagnosis from controllers but should not be held to be regular sources of cognitive resources consumption.

This partition is important in as much as the workload reduction induced by the introduction of the ERASMUS solver can be graphically caught. The differences between Figure 9 and Figure 10 demonstrate the benefits of ERASMUS, for each of the three levels, as follows. With ERASMUS, aircraft pairs which fall below the separation are more clear cut, in the sense that the minimal horizontal distance is always below 3Nm (with one isolated exception), and the ATCO anticipation is roughly between 3 to 5 minutes. On the other hand, without ERASMUS, the same level is sparser, both for the minimal horizontal distance and for the ATCO anticipation. The range of 3 to 5 minutes seems to appear as the "ideal" range, from the ATCO viewpoint, and deviations from that range can be interpreted as a less efficient ability, for her/him, to schedule work.

As for the yellow "area of ATCO doubt", the introduction of ERASMUS results in a massive decrease of the ATCO instructions. The variation of the anticipation is similar to the previous case, and strengthens the previous observation, that the range from 3 to 5 minutes seems to be ideal in terms of trade off between time pressure and uncertainty.

The third level, which is the "area of ATCO comfort", shows a higher dispersion of the ATCO anticipation with ERASMUS. This is consistent with a less constrained scheduling for these tasks.

The two last Figures give precious information about which encounters (i.e. associated with certain virtual separation values) are considered as conflicts by ATCO and when they are resolved (anticipation). This last information corresponds to the right boundary of maturing time in Figure 2 (the left one being the time of the risk perception). This already gives a meaningful picture of ATCO decision process and, more globally, of how their expertise concretely expresses itself. A future step for processing these data could be to investigate the whole maturing time interval – and not only its "right limit" – since it provides a substantial part of mental load. By doing so, a more complete model of workload would be generated and further be used in the future ATM projects. On the way to more automated ATC, a transition phase (human/ machine collaboration in high level processes) will exist, be crucial and require an accurate knowledge of the basic skills of air traffic controllers.

IV. CONCLUSION

In this paper we have presented how the introduction of the SESAR ConOps implies a change in:

- the hazardous events which need to be identified, mitigated and monitored;
- the safety criteria;
- the (safety) assessment of human performance in ATM;

for the management of ATM safety.

The hazardous events will be related to encounters, systems failure (including human failure), and human performance at individual and organization levels. The major changes are the forecast increase of systems failure frequencies in the split of events, and the new human/machine split for the prevention of encounters. One key issue will be to identify among these events those which result from an error propagation in the ATM system or from a common mode of failure.

The mitigation measures to prevent these particular events will presumably be handled by pilots or ATCOs, and will change their work profile and workload. In order to assist them new automated tools will be developed, thus increasing the complexity of the ATM system.

In the past the main tools for managing safety in ATM were separation distances, initially designed to mitigate position errors. Historical experience has shown that the implicit safety margins provided by separation distances were also sufficient, in the pre-SESAR context, for the mitigation of all other causes of ATM hazards.

This may not be true with the SESAR ConOps and a new set of safety criteria may need to be developed in order to define safety objectives for individual systems and organizations, and safety indicators to verify that the required safety performance is met. This new challenge will require a continuous cooperation of systems engineering, human factors and safety experts.

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