Integrating human factors in the design of intelligent systems: an example in air traffic control

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Abstract: In the current organisation of air traffic control, some cooperative activities appear in the work of air traffic controllers, especially between Tactical Controllers (TC) and Planning Controllers (PC), who manage aircraft inside a sector to prevent collisions. These cooperative activities allow building and maintaining a Common Frame of References (COFOR) to be built and maintained. The COFOR is an internal representation of the situation, and introducing specific assistance based on this COFOR not only improves the effectiveness of the human activities, but also improves the controller's situation awareness and the human–machine cooperation. This article presents a study of a project called Automation and MAN–machine Delegation of Action (AMANDA), which proposes assistance to the controllers for resolving aerial conflict. In order to avoid decisional conflict between human operators and the assistance system, AMANDA integrates human strategies for calculating new trajectories that which avoid conflicts and communicates with controllers through a Common Work Space (CWS), which is a physical representation of the human operators' COFORs. This study took place in three steps. The first step, based on an experimental investigation, allowed the content of the COFOR to be defined. In the second step, the CWS supporting human–human and human–machine cooperation and the characteristics of the support tool were defined. In the last one, the proposed principles were evaluated by professional air traffic controllers.

Keywords: adaptive automation; air traffic control; CWS; Common Work Space; DTA; Dynamic Task Allocation; human factors; human-centred design; human–machine cooperation; intelligent system design; task delegation.

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1 Introduction

This article deals with human–machine cooperation in the domain of air traffic control (ATC) in which highly dynamic situations appear. These situations subject the air traffic controllers to strong workload variations. This context is made more complex by the increase in air traffic.

One way to maintain the same level of security is to introduce support tools into the human–machine system in order to regulate the air traffic controllers' workload. Several kinds of support tools have been evaluated in the ATC domain. Our approach consists of introducing basic action assistance in order to reduce the controllers' workload, while maintaining controller competencies for performing complex tasks. Our research focuses on the problem of dynamic task allocation (DTA), which consists of dynamically allocating tasks to be performed to human operators and/or to one or several support tools, (Debernard et al., 1990; Vanderhaegen et al., 1994).

In this article, we first present the general principles related to Human-Machine Cooperation (HMC). We also present some previous research that evaluated the DTA between air traffic controllers and a support tool that was able to resolve some conflicts between aircraft. The results obtained showed that DTA principles allow the human workload to be regulated. However, to obtain efficient HMC, it is necessary that

1 all the agents (human and artificial) share the same representation of the situation, and

2 the support tool takes into account the strategies of the human operators in order to avoid decisional conflicts between these operators and these support tools.

In section 3, we present our project, called Automation and MAN–machine Delegation of Action (AMANDA). This project evaluates the principle of task delegation in which a support tool performs some tasks based on a strategy defined by the controllers. Before designing the support tool, we conducted some experiments in order to characterise the functions that would be allocated to this support tool and the human-machine interfaces. These interfaces must allow the controllers and the support tool to share the same representation of the situation.

This study took place in three steps:

- First, based on an experimental investigation with professional controllers, the content of the COFOR which is a common internal representation of the situation, was identified.
- Second, the Common Work Space (CWS), which supports human–human and human–machine cooperation, and the characteristics of the support tool were defined.
- Third, the proposed principles were evaluated by professional controllers.

The results of the third step (i.e., the evaluation) are presented later in this paper. This study was completed in collaboration with the CENA (French Air Navigation Study Center).

2 Human-Machine Cooperation

One step in complex system design is the choice of the appropriate level of automation (Riera and Debernard, 2003). This step is difficult because the human needs must be considered precisely. Too much automation can, in the long term, degrade the human operator's abilities, and, in the short term, can generate problems for the operator because he/she can have difficulty obtaining a good 'picture' of the process when a failure occurs. On the other hand, too little automation can be insufficient to maintain overall system reliability and productivity, because the human operator can be overloaded situation (Garland, 1991).

Automation can be achieved through two main approaches:

- The first one consists in defining the function allocation between the human operator(s) and one or several control systems: the tasks or subtasks to be performed are definitively allocated to agents according to their abilities and their 'limitations', (Hollnagel and Bye, 2000; Sheridan, 2000).
- The second one focuses on HMC, which can be complementary to the first approach.

HMC is a multi-disciplinary field of research. Some researchers are interested in describing and understanding the psychological mechanisms underlying cooperative activities; others are interested in defining tools and human–computer interfaces to support for supporting these cooperative activities. Hoc (2001) states that

> "Two agents are in a cooperative situation if they meet two minimal conditions:
>
> - Each one strives towards goals and can interfere with the others on goals, resources, procedures, etc.
> - Each one tries to manage the interference to facilitate the individual activities and/or the common task when it exists.
>
> The symmetric nature of this definition can be only partly satisfied."

In Hoc's definition, the notion of goal does not refer to the global goal of supervising and/or controlling a process, but to the goal for a particular task. The word 'interference' refers not only to the normal interaction between the activities of several agents, but also to conflicts between the agents about results of their activities, or about the means of accomplishing their tasks.

For Millot and Lemoine (1998), each agent is characterised not only by his/her know-how, but also by his/her know-how-to-cooperate. The know-how is necessary for solving problems and performing tasks autonomously, gathering problem-solving capabilities (source of knowledge and processing abilities) and communicating with the environment and other agents through sensors and control devices. Know-how-to-cooperate serves two main functions: to allow agents to manage interference (e.g., between their goals and/or resources) and to allow agents to perform their own activities, while also taking into account the activities of the other agent(s) in order to facilitating them.

Clearly, in HMC, it is necessary to improve the interactions between agents that allow the agent to accomplish their tasks correctly while minimizing the potential conflicts. However, Hoc's definition shows the limits of HMC, especially if the 'machine' or computer must facilitate the human activities, because it will be necessary to prevent or detect conflicts with the human operators.

Royer (1994) asserted that a system is more cooperative when this cooperation integrates several levels: perception, analysis, decision and action. So, cooperation is not only the coordination of actions between several agents, but also depends on the merging of perceptions, the confrontation of situation analyses, and the convergence of decisions.

To model such interaction, it is possible to use the three kinds of cooperation defined by Schmidt (1991):

- *Augmentative cooperation*: cooperation is augmentative when agents have similar know-how and perform several similar tasks when the load is too high for only one agent.
- *Integrative cooperation*: cooperation is integrative when agents have different and complementary know-how, and it is necessary to integrate their contribution to accomplish a task.
- *Debative cooperation*: cooperation is debative when agents with similar know-how are faced with a single task, and they compare their results in order to obtain the best solution.

For Grislin and Millot (1999), any cooperative situation can be described as a combination of these three forms. But, these authors consider that tasks (or sub-tasks) are performed entirely by agents, even if there is some interaction between them before or after the task is completed, depending on the form of cooperation. But it is possible to extend this idea by taking into account the activity level instead of the task level (Debernard and Hoc, 2001).

Dynamic Task Allocation (DTA) is initially an augmentative form of cooperation. DTA consists of assisting the human operator, first by integrating an automated system that is able to perform some tasks, and second by allocating the tasks to each agent dynamically. So, the automated system must integrate all the functions that are needed to perform a task entirely, from 'information elaboration' to 'solution implementation' (Debernard et al., 1990).

An optimal DTA aims to find a level of task sharing that optimises the process performance and that takes into account both decision-makers' abilities and capacities. Thus, an optimal DTA allows the level of automation to be modified dynamically in order to keep the human operators 'in the loop'.

In a previous study called SPECTRA (Debernard, Vanderhaegen and Millot, 1992; Crévits et al., 1993), DTA was implemented between the TC and an assistance tool called SAINTEX, which is able to resolve simple conflicts between only two aircraft (i.e., without other interfering aircraft in the same space). SAINTEX (Angerand and Le Jeannic, 1992) has its own strategy and performs completely the resolution task completely, from conflict the detection to instruction implementation, including re-routing.

Several modes of DTA have been evaluated. The main result of these experiments (Debernard, Vanderhaegen and Millot, 1992) is that DTA seems to improve the air traffic control task and to reduce the overall workload. Still SPECTRA highlighted the problem of controller acceptance of the assistance. Because controllers had a limited level of trust in SAINTEX, they wanted to maintain control with the possibility of taking back conflicts previously allocated to SAINTEX (Hoc and Debernard, 2002). But, an activity analysis showed that cooperation between the agents was more operational: the assistance tools seemed to make the controllers' activities better planned and less reactive to events because it allowed reducing the human cognitive workload to be reduced (Lemoine et al., 1996; Hoc and Lemoine, 1998).

One of the main points highlighted by these results is the importance of the information carried on graphic displays. These information constitute a reduced CWS, in which SAINTEX and controllers could display symbols to mark important information, especially the conflicts detected. Because controllers are used to working together, and because they display a subset of their understanding of the situation on the reduced CWS, each controller does not need to communicate all the time with the other for making a decision. However, this reduced CWS is insufficient because it does not integrate all the 'results' of the controllers' activities, such as information elaboration, diagnosis, or decision making.

Another problem is that the strategy adopted by SAINTEX can hamper controllers because they do not share the same representation of a conflict. In fact, SAINTEX has its own strategy, and TC can take into account another aircraft in the conflict in order to resolve the conflict in accordance with his/her abilities and workload.

The following section presents the AMANDA project, in which a 'real' CWS was been defined and implemented to resolve the problems mentioned above.

3 AMANDA project

3.1 From Dynamic Task Allocation to task delegation

The AMANDA project concerned the study, implementation and evaluation of a support tool that would be more cooperative than SAINTEX (Debernard et al., 2002). The human–machine cooperation mode proposed in AMANDA was the delegation of tasks to the support tool. The difference between DTA and task delegation is that, with the former, the support tool perform the shareable task entirely on its own, whereas with the latter, it performs the task according to a strategy designed by the human operator.

The goal of this type of human–machine cooperation is the same as DTA: to reduce the human workload, thus giving the human operator time to focus on complex situations that the support tool cannot deal with.

This approach poses a fundamental difficulty in that the air traffic controller is supposed to provide a strategy to the support tool when, in fact, the problems (or situations) are not always well enough defined to allow a strategy to be developed. Before a human operator can produce a final decision (i.e., an operational decision that can be applied to the process), this decision has to progress from a schematic decision (i.e., a strategy in an embryonic state) to the final decision, following several finetuning steps (Figure 1). This finetuning includes the progressive introduction of constraints that will reduce the freedom degrees of the decision, defining the process situation more and more precisely. In the case of air traffic control, this finetuning also includes controllers taking the uncertainties (e.g., meteorology) of the situation into account.

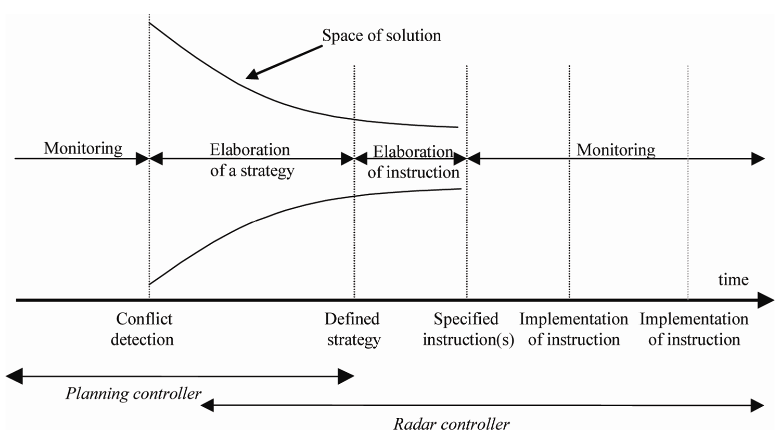
So, the cooperation between human operators and the support tool must be designed to take several kinds of human decisions into account, not only those delegating tasks to the support system, but also those defining the interaction between the two controllers (TC: Tactical Controller; PC: Planning Controller) and the support system in consideration of the work rules.

To predict TC's workload in order to avoid future overload, the PC must detect the future problems in their sector. For example, when the PC detects a conflict with two or more aircraft, he/she must inform the TC who then resolves the conflict. In other words, the PC 'prepares' the traffic for the TC. We think it is possible to provide the means for better human–human cooperation between the controllers. Figure 1 shows a possible linking of the two controllers' activities.

The dialogue support – the human–machine interface – must be well studied, first, to allow the problems and strategies defined to be easily introduced into the support tool, and second to improve the cooperative activities between the agents. So, the AMANDA project concentrated on designing:

- the know-how of the support tool, and
- a CWS capable of supporting the interaction between the two controllers and between the controllers and the support tool

Figure 1 Finetuning a human decision for two air traffic controllers



3.2 A Common Work Space to support human–machine cooperation

In order to characterise the content of the Common Work Space (CWS), it is necessary to study the interactions between the functions and the human activities.

Many disciplines have already worked on the CWS idea (Bentley et al., 1992; Decortis and Pavard, 1994; Jones and Jasek, 1997). For example, in the case of Air Traffic Control, Bentley et al. (1992) have presented a shared work space that provides an adapted presentation of air traffic to different users, on different machines, to make the use of shared entities easier. Decortis and Pavard (1994) have defined the shared cognitive environment as a set of facts and hypotheses that are a subset of each agent's cognitive universe.

To define the CWS, it is possible to start from a model of human activities. The Rasmussen's model (1983) includes four main activities: information elaboration, situation identification, decision-making and solution implementation. According to Hoc (1996), the human agent plans her/his own activity in order to manage her/his internal resource with respect to the time pressures and stress affecting him/her. To manage situations, the human agents build a frame of reference containing different attributes (Pacaux-Lemoine and Debernard, 2002): information (stemming from information elaboration activities); problems (stemming from identification activities); strategies (stemming from schematic decision-making activities); solutions (stemming from precise decision-making activities); and commands (stemming from solution implementation activities) (Figure 2). In turn, to cooperate, these agents pass on information, problems, strategies, solutions and commands in order to share their own frames of reference, thus building a virtual COFOR (Carlier and Hoc, 1999).

Figure 2 Contents of a Common Frame of References

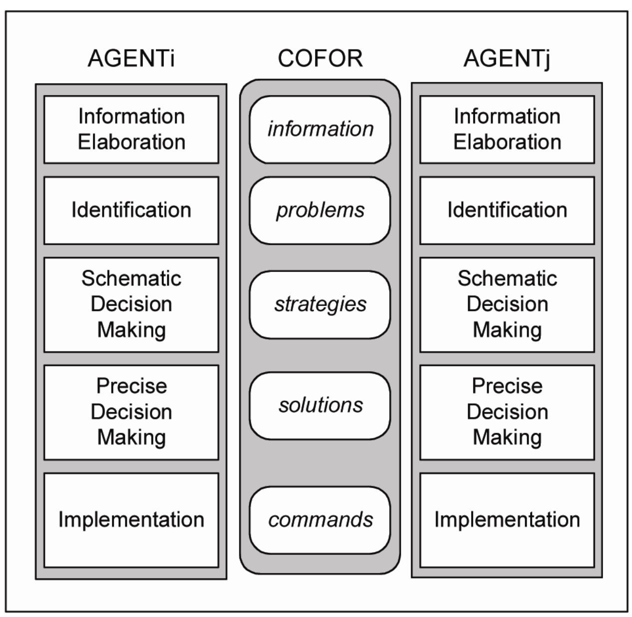
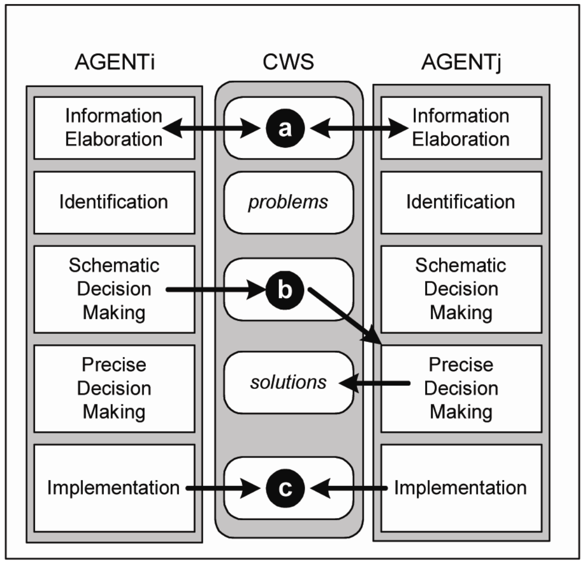


Figure 3 Inter-agent cooperation using a Common Work Space



In HMC, the CWS is the physical representation of the COFOR, and can be the support for cooperation between the human agents and the artificial agents. But, it is necessary to define which activities/functions will be performed by the different types of agents and which form of cooperation will be implemented. To do so, it is possible to use Schmidt's three forms for characterising the cooperative activities around the CWS. In the debative form (Figure 3a), all the agents supply the CWS with new data (for one task and for one activity/function), and when interferences appear, the agents can negotiate. In the integrative form (Figure 3b), only one agent supplies a data for the CWS, and the other one takes these data into account when performing the next activity/function. In the augmentative form (Figure 3c), the agents all perform the same activity/function and update the CWS, but with different tasks, according to the task allocation.

The design of a cooperative human–machine system requires that the effective content of the CWS be defined according to the domain and the tasks to be achieved. Moreover, the use of a CWS generates new activities from human agent, but also new functions from an assistance tool, in order to manage the CWS; these activities/functions are the same ones used to build and maintain the COFOR (Pacaux-Lemoine and Debernard, 2002):

- *Updating the CWS*: from their own individual frame of reference, all agents (human or artificial) perform some activities/functions in order to update the different attributes of the CWS.
- *Controlling the CWS*: all agents perform some activities/functions in order to compare the CWS with their individual frame of references in order to detect interferences on one or more attributes. These are mutual control activities.
- *Managing the interference*: first, the activity corresponds to a diagnosis of the differences between each individual's frame of references, and then the interference must be resolved.

Three forms of resolution can be used by the agents: negotiation, acceptance and imposition. These forms imply different cognitive and communication costs for the human agent. Negotiation aims to reduce the differences between the CWS and an agent's frame of reference by modifying one of them on the basis of the explanations of the different agents. Acceptance is chosen when the cost of negotiation is too high or when an agent wants to facilitate the activities of the other agents. Imposition is the opposite of the acceptance.

The implementation of a CWS between a support tool and one or several human agents brings some constraints into play, in particular for negotiation. Two human agents, when they negotiate, may use symbolic explanations, which are very efficient. An artificial agent, however, needs an explicit explanation based on operational information. So, at present, it is very difficult to implement the capacity for real negotiation with human agents in an artificial agent.

In order to define the characteristics of the support tool and the CWS, an experiment was conducted with professional controllers from the Regional Control Center (RCC) in Bordeaux (France). This experiment was called AMANDA V1 and corresponds to the first step of our study.

4 Step 1: an experiment for defining a the Common Frame of Reference in ATC

An experimental platform, with a realistic air traffic simulator, but without support tool, was developed for this experiment (Guiost et al., 2003). Two kinds of experiment were performed on this platform. The first one was called *anticipation* and the second was called *cooperation*.

In the first experiment, the sector was managed by two controllers: TC and RC. The experimental method consisted of stopping periodically the simulation periodically to ask the TCs to anticipate their traffic management decisions. During the experiments, all data coming from the platform was recorded as the verbal communication between controllers in order to perform a cognitive activity analysis. Seven pairs of professional controllers participated in this experiment. This *anticipation* experiment (Morineau, Hoc and Denecker, 2003) produced two main results that allow the functions of the support tool to be characterised:

- To obtain efficient human–machine cooperation, the support tool must be integrated into the controller's space-problem so that the information representations are the same for all the decision-makers. The support tool must also allow controllers to build this space-problem as they want, even if the support tool detect interference in this representation of the situation. For example, if a controller introduces a strategy into the support tool, and the tool can detect another aircraft that will interfere with the solution. So, the support tool must supplement the space-problem.
- The support tool must allow controllers to focus on a particular problem. But, to prevent controllers from losing sight of the global situation, it is best to present the problem on the display in the format of the radar image, including all the aircraft. The aircraft included in a problem are highlighted in colour, while the other aircraft are grey.

The second experiment, called cooperation, was designed to determine the form of dialogue between the two controllers and the future support tool (Guiost et al., 2003). For this purpose, one PC and two TCs managed the same traffic together. A static allocation of the aircraft was established for the two TCs, in which one TC could not send any instruction to an aircraft allocated to the other controller. This type of allocation was chosen to force controllers to cooperate on the same conflict. Six teams of three controllers (two TC and one PC) participated in this experiment.

A cognitive task analysis was performed based on verbal exchanges between the two TCs. The encoding used the predicates corresponding to the different activities linked to the COFOR. Four predicates are used for encoding verbal exchanges: SIMPLE SUPPLY, SIMPLE REQUEST, INTERFERENCE DETECTION and INTERFERENCE SOLUTION. The two first predicates translate the activities used to build and update the COFOR. INTERFERENCE DETECTION corresponds to the detection of interference between a controller's frame of reference and the COFOR. Finally, INTERFERENCE SOLUTION corresponds to activities that reduce the difference of one or more attributes between the frame of reference of a controller and the COFOR.

All of those predicates contain four arguments: controller, problem number (conflict), item (COFOR attribute) and variable. In addition, INTERFERENCE SOLUTION contains the method used to reduce interference: NEGOTIATION, ACCEPTANCE and IMPOSITION.

One item and several variables are attributed to each predicate according to the content of verbal exchange. Items are 'data', 'problem', 'strategy', 'solution' and 'implementation' and correspond to the COFOR attributes. Table 1 shows some examples of the exchange between the two controllers and the results of the encoding.

The results of the cooperation experiment are summarised below (Guiost et al., 2003):

- 58% of the predicates are SIMPLE SUPPLY compare to 15% of SIMPLE REQUESTS (Figure 4). This result implies a strong activity of COFOR development and maintenance of the due to spontaneous contributions of information.
- The distribution of the various interference resolution methods indicates 58% are imposition, 19% are acceptance and 23% are negotiation (Figure 5). The detail on the types of interference resolution shows that the items mainly concerned by impositions are data, problems, solutions and implementation (approximately 65% of the resolutions concern these items). 'Imposition' and 'acceptance' are less expensive which are less expensive than negotiation given a context of heavy traffic. On the other hand, the main item concerned by negotiation is the item, 'strategy' (75%).

Table 1 Examples of exchange between the two controllers and the results of the encoding

Controller	*Verbal exchange*	*Time*	*Predicate*	*Problem number*	*Item*	*Variable*
RC 1	Look at AFR and IEA	09:10:28	SIMPLE_SUPPLY	7	problem	AFR111, IEA456
RC 2	Turn AFR behind IEA	09:10:38	SIMPLE_SUPPLY	7	strategy	AFR111, IEA46, « Turn behind »

Figure 4 Predicate distribution

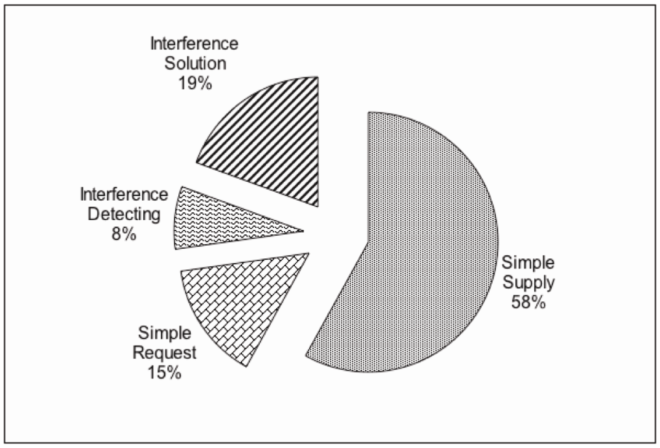
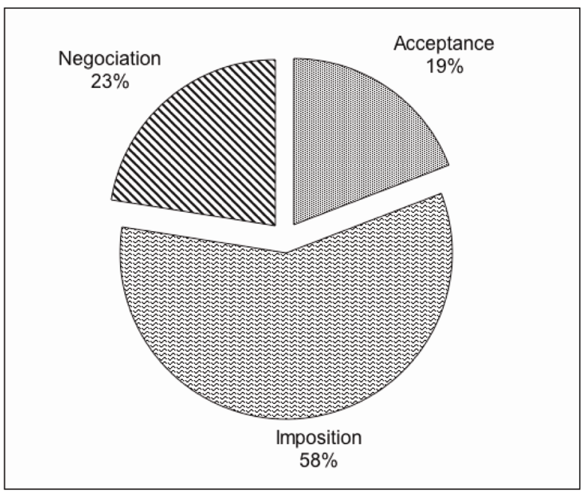


Figure 5 The interference resolution method distribution (interference solution)



However, as Figure 6 shows, the behaviour of the controller triads. The top part of the figure shows the distribution of the items by predicates for one experiment is presented. The majority of the predicates are linked to SIMPLE SUPPLY for the data and the problems, though a few INTERFERENCE DETECTION and INTERFERENCE SOLUTION appear. However, the bottom part of this figure shows a different behaviour. The SIMPLE SUPPLY for the data and the problems are less numerous, leading to an increase in INTERFERENCE DETECTION and INTERFERENCE SOLUTION.

To understand these behaviours, a temporal analysis was done to evaluate whether or not controllers managed the situations correctly. In order to allow all the data to be analysed together, all dates of predicates linked to a problem were set relative to the absolute hour of this problem, defined for an experiment without controllers and corresponding to the safety net activation (alarm) for this problem. Then, the temporal space of the problem is divided into five 5-minute zones (Figure 7).

Figure 6 Distribution of the items by predicates for two trinomials triads

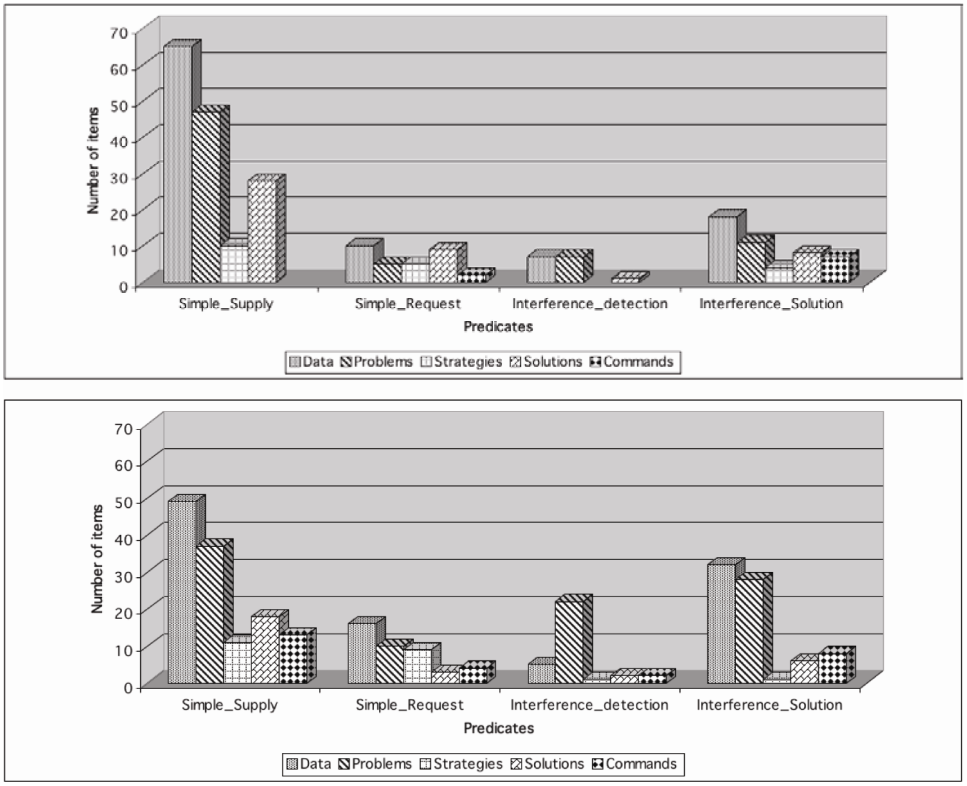
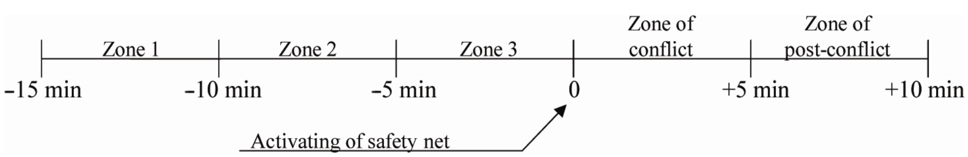


Figure 7 Distribution of the problem's temporal space



This temporal analysis shows that the controllers built their reference frame relatively early, with consequences on the number of interferences. In particular, certain controllers emitted a great number of SIMPLE SUPPLY and a small number of INTERFERENCE DETECTION during the first zones (Figure 8). This example indicates a good anticipation of the situation, which results in a very low number of interferences in the resolution of the conflicts.

Figure 9 illustrates a lack of anticipation and the consequences that such a lack engendered for the traffic. The controllers do not communicate a lot during the first two zones (1 and 2). It is only in zone 3 that the controllers start to deal with the problems. Previously, the controllers had not worked out and had not structured their problems. They pay for this lack of foresight in terms of interferences in the conflict zone, (i.e., in the critical zone from the point of view of control), which is serious with respect to problems of safety.

Figure 8 Positioning of the various predicates according to relative time- triad 1

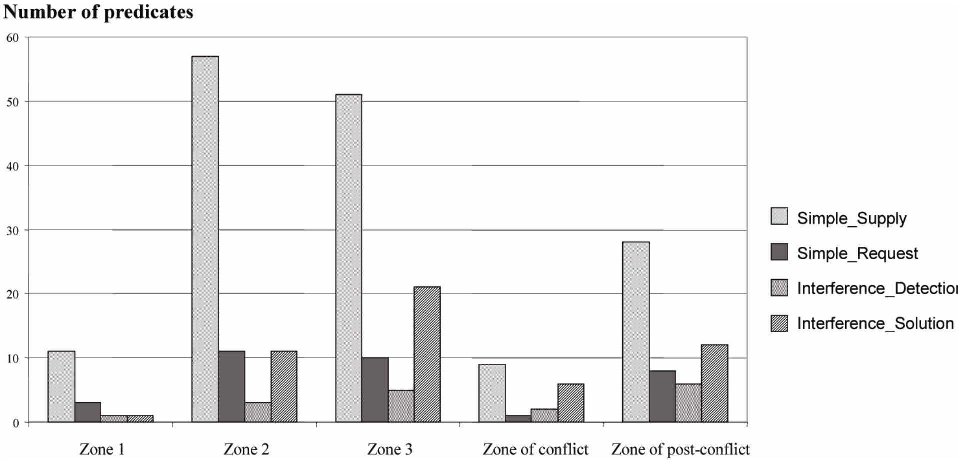
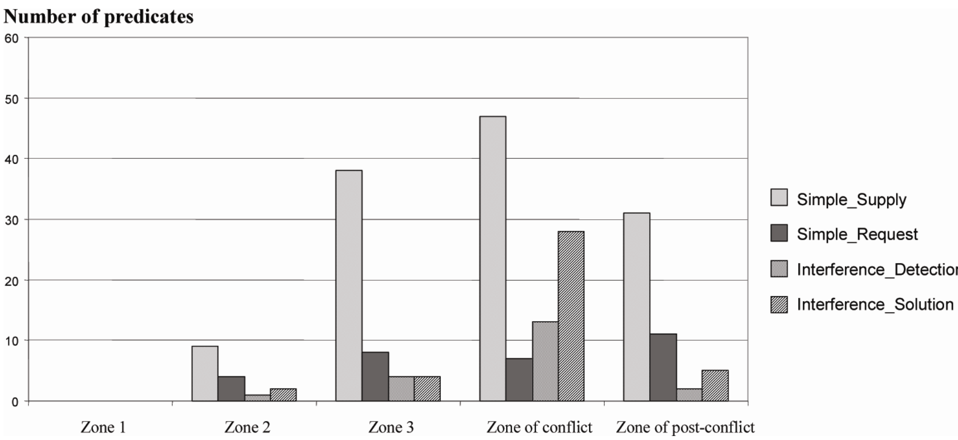


Figure 9 Positioning of the various predicates according to relative time- triad 2



The AMANDA V1 experiments allowed us to characterise the functions of the future support tool for task delegation and the interaction between controllers and this support tool, which will be supported by the human–machine interface. These experiments have shown that when human operators must cooperate, they build and maintain a COFOR. To obtain efficient human–machine cooperation, it seems to be necessary to implement this COFOR. The next section of this article describes the functions of the support tool, called STAR, and the contents of the CWS.

5 Design of AMANDA

The new platform called AMANDA V2 includes two main modules: STAR (French acronym for resolution assistance system), the support tool for task delegation, and the CWS. STAR must perform several functions and must also interact with the controllers

(Debernard et al., 2002). The contents of the CWS were defined in the AMANDA V1 experiments. In Table 2, each line in the first column refers to a human activity; for each activity is shown:

- the generic information produced by the activity/function, and
- the effective contents of the CWS for the ATC domain.

A problem is a set of conflicting aircraft and is called *cluster*. A cluster is composed of at least two aircraft in a duel situation (binary conflict) and other aircraft that can interfere with this duel. An aircraft interferes with a duel if the resolution of this initial duel generates another duel. A cluster (the aircraft included in this cluster) is defined by the controllers, because the definition can depend upon the controllers' strategy.

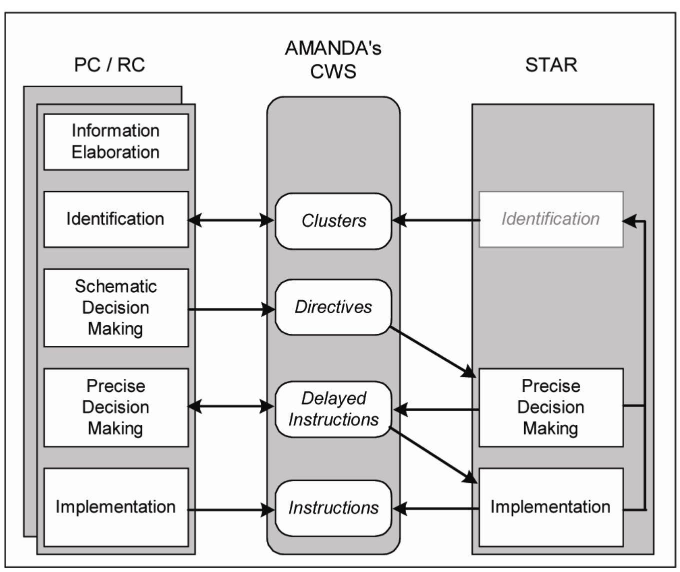
A strategy is modelled as one or several *directives* for resolving a problem. For example, a directive can be "turn AFR365 behind AAL347". So a directive does not indicate a place and a value as is the case with a normal instruction. Directives are also defined by the controllers, in accordance with the delegation principle. A solution is a delayed instruction; for example, "turn AFR365 30° to the left at 22 : 35".

Using the contents of the CWS, the function of STAR and the interaction between STAR and the two controllers may be specified (Figure 10).

Table 2 Common Work Space (CWS) of AMANDA V2

Human activities	*Information*	*Contents of CWS*
Elaboration of information	Initial information	None
Detection	Problems	Cluster
Schematic decision making	Strategies for resolving a problem	Directives
Precise decision making	Solutions	Delayed instruction
Implementation of solutions	Solutions implemented	Instruction

Figure 10 Functions of STAR and interactions with controllers



From a directive given by controllers, STAR is able to calculate a new trajectory for an aircraft in order to resolve a duel. This new trajectory is composed of one or several delayed instructions. Nevertheless, STAR, based on the new trajectory, can detect a new duel with interfering aircraft. The new trajectory is entered into the CWS and the interfering aircraft is added to the cluster to warn the controllers. The warned-against situation could appear if the controllers do not see the problem (the interfering aircraft), or may likely appear if the controllers have not yet added all the directives (the strategy) for resolving the conflict.

Based on a delayed instruction given by the controllers or calculated by STAR, the tool is able to monitor and implement this delayed instruction, if this function is delegated to STAR. But before implementing an instruction, STAR verifies that the delayed instruction will not generate any duel. In this case, the interfering aircraft is added in the cluster.

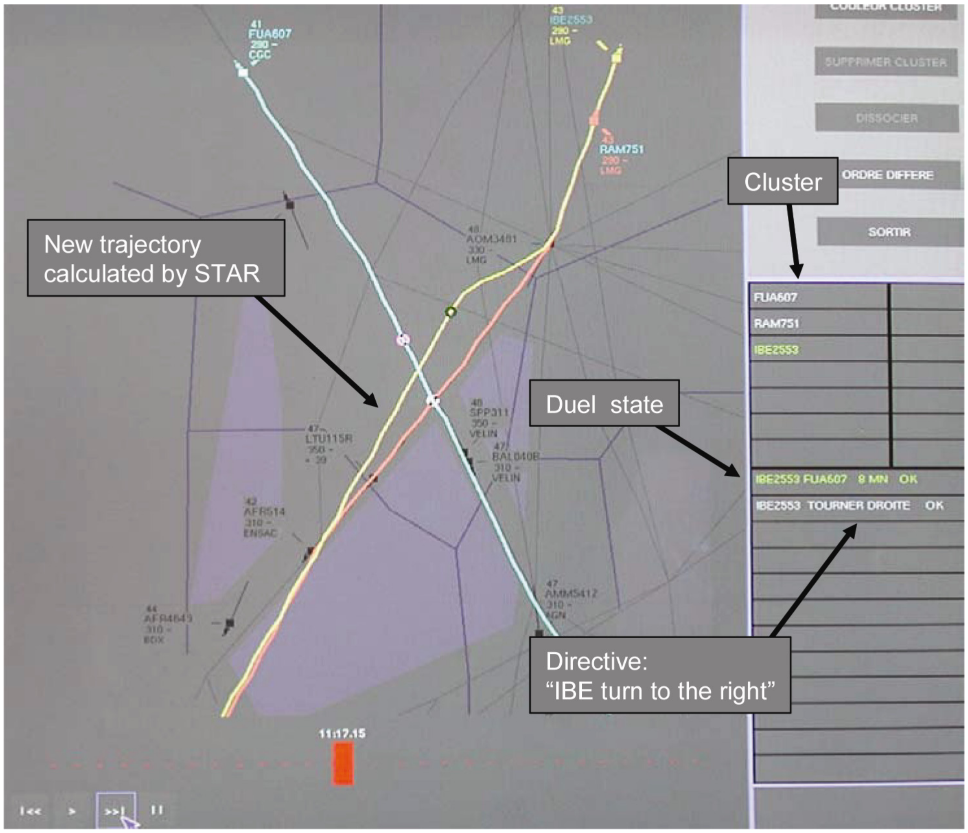
From the point of view of human–machine cooperation, the project AMANDA allows the three modes of cooperation defined by Schmidt (1991):

- Augmentative mode: STAR is able to perform some parts of the solution tasks if so instructed, particularly the implementation function that requires a monitoring function. So, controllers and STAR perform the same activity/function but for different problems.
- Integrative mode: STAR takes into account the strategy and/or the solution provided by controllers to perform the functions necessary to resolve a problem completely.
- Debative mode: STAR is able to modify the controllers' perception of a problem when STAR detects interfering aircraft that are not part of a defined cluster. In the direction, the controllers are able to take into account the solutions calculated by STAR, but can also integrate into the CWS another directives or constraints if they do not agree with STAR's solution.

Thus, the CWS allows controllers to "negotiate" with STAR, because it is possible to add new directives to a cluster. It is also possible to add geographical constraints to a directive, or to indicate that STAR should not take into account an interfering aircraft into account when calculating a new trajectory, leaving the controllers to manage this aircraft alone.

AMANDA V2 includes all these concepts. This platform is composed of several workstations, which support a realistic air traffic simulator, STAR, and two HMI for TC and PC. Each of workstation has two screens. The first displays a radar image; the second shows the CWS, which is composed of two views which can be swapped by controllers. On the first view are presented all the clusters defined by controllers. In each cluster, not only the aircraft are displayed, but also the directives given by controllers and the delayed instructions calculated by STAR. When a controller selects one cluster, a resolution view is displayed (Figure 11). This view allows controllers to add information in the CWS but only for the concerned cluster, such as aircraft, directives and delayed instruction. For each aircraft, the predicted trajectory is displayed in accordance with all the delayed instructions given by the controllers or calculated by STAR.

Figure 11 The resolution view (see online version for colours)



The goal of STAR is to give to the controllers the most relevant trajectory according to a given strategy (Cathelain and Debernard, 2000). The strategy is formulated by the controller in the form of a directive that includes the aircraft involved in the conflict, the conflict resolution mode, some constraints on the beginning and the ending of the resolution, among other elements. All the resolution modes included in STAR result from the AMANDA V1 experiment, designed to match the controllers' resolution strategies. The constraints contained in a directive reduce the possible solution space, but this space still contains a lot of solutions. There are two steps to reduce this solution space to one solution.

There are two steps to reduce this solution space to one solution:

- The first step is a partial exploration of the solution space (targeted exploration). To explore this space, the support tool calculates a set of possible trajectories. To limit the number of solutions, the support tool calculates trajectories with a time step of separation between them.
- The second step is a multi-criteria choice resulting in the most relevant trajectory with respect to a set of specific criteria: the preferences of the decision-makers, the safety offered by taking into account a minimal separation distance between aircraft, the number of instructions, the number of deviations, and the greatest deviation.

6 Experiments

In order to assess the impact of this type of support system on controller activity, six professional controllers tested AMANDA V2. Each pair of controllers worked with the new support system for two days, in two phases. In the first phase, they familiarised themselves with the system, participating in several training scenarios that allowed them to gradually discover the various system functions. In the second phase, the controllers used the support system in three different situations, selected with the aim of evaluating the effectiveness and the relevance of the various modules of the tool (Guiost et al., 2006).

In the first situation (A), the STAR computational solution tool was disconnected, and the two controllers had to rely on the CWS for any cooperative activities. In the second and the third situations (B and C), the entire support system was available, and the goal was to determine the best way to share the various tasks between PC and TC. In situation B, the PC was responsible for building the clusters and defining strategy, and the TC had to decide whether to accept, modify or refuse the new trajectory calculated by STAR. If the TC accepted the strategy, he/she could then delegate it to STAR. However, the TC could also define a new strategy and delegate its application once the STAR calculation showed the new strategy was appropriate. In situation C, the PC was still responsible for building the clusters, but it was the TC who defined the problem-solving strategies and delegated them, if necessary.

The experiments were organised according to an experimental plan that crossed the situations, the order of appearance of these situations, and the traffic scenario used in each situation (Table 3). Three pairs of professional controllers took part in the experiments, and the scenarios included double the usual number of aircraft.

Because of the low number of controller pairs participating in the experiments, it was not possible to obtain reliable results using statistical methods. In order to mitigate this problem, the responses to Task Load Index (TLX; Hart and Staveland, 1988) questionnaires for evaluating global workload were studied using Wilcoxon's test to highlights any significant differences between two series of measurements of the same variable. This test showed no significant difference in the TLX workload between the various traffic scenarios encountered by the controllers or between the various orders in which participating controllers encountered the three situations. On the other hand, although the differences in the workload between the situations A and B and the situations B and C are not significant, there is a significant difference between the situations A and C. The controllers apparently perceived a much heavier workload in the latter situation than in the former. The Situation B did not cause this perception of extra work. Thus, situation B appears to provide a good compromise in terms of tool use and the distribution of tasks between the TC and the PC.

The best performances in terms of fuel consumption were noted for situation A (i.e., when STAR was disconnected). This observation should be interpreted in context, since though situation A demonstrated better performances than situations B and C in 66% of the cases, the difference was only from 1 to 2%. This can be explained simply by the sedentary nature of the support system. In truth, the STAR tool makes its calculations with a safety margin of a minimum distance of 12 nautical miles, whereas the standard is 6 nautical miles.

Table 3 Experimental plan

	Test 1	*Test 2*	*Test 3*
Pair 1	Situation A	Situation B	Situation C
	Scenario E1	Scenario E2	Scenario E3
Pair 2	Situation B	Situation C	Situation A
	Scenario E3	Scenario E1	Scenario E2
Pair 3	Situation C	Situation A	Situation B
	Scenario E2	Scenario E3	Scenario E1

Scenario	*Effective duration*	*Number of aircraft*
E-1	45 min	37
E-2	45 min	42
E-3	45 min	36

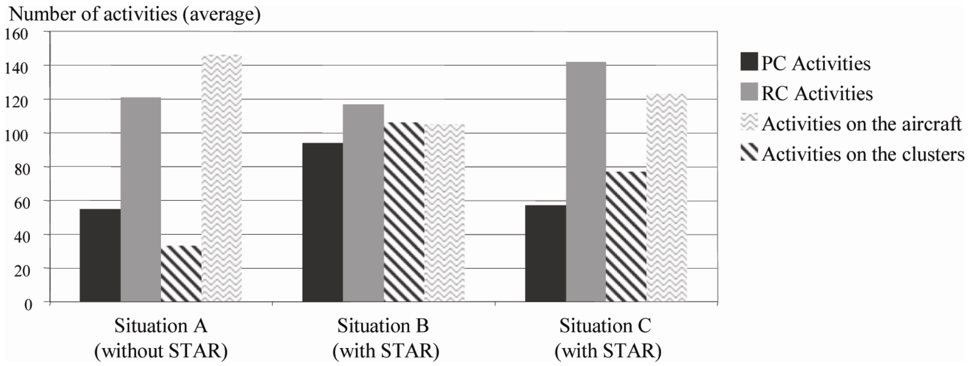
For all three situations, a very large majority (93%) of the conflicts led to the creation of at least one cluster. In situations B and C, 75% of the clusters were associated with a directive or a differed order. Of those, 63% were delegated to STAR, but only 24% of them were completely delegated. In fact, STAR sent an initial heading instruction to the aircraft and then sent a subsequent instruction to set the aircraft on its initial route (direct). But in many cases, TCs prefer to send a direct earlier than STAR, which requires a minimum distance of 12 nautical miles. However, this behaviour shows that the controllers ensure the correct monitoring of the conflicts.

Studying directives according to situations shows that the controllers logged the most directives/differed orders during situation B (85% as opposed to 65% for situation C). The most delegated solutions were logged during situation C (56% as opposed to 41% for situation B). However, it was during situation B that controllers delegated the solutions to STAR the most completely (30% for the problems with two aircraft and 45% for those affecting three aircraft).

In order to assess the activity transfer that occurs between the controllers themselves and between the controllers and the support system, all of the activities involving the aircraft or the CWS were collected and classified according to situations. An activity on an aircraft might be, for example, a heading instruction or transferring the plane to an adjacent sector. An activity on the CWS might be, for example, creating or deleting a cluster or adding information to an existing cluster. According to situations Figure 12 presents the PC's and TC's activities according to the situations (i.e., all the instructions/actions that the controllers gave/took on the aircraft or on the CWS). This figure also shows the activities related to the flights and to the CWS, independent of the type of controller.

There was less activity on the CWS during situation A than during the two other situations. This is normal, given that STAR was disconnected. However, the activities of the TC and those of the PC are unbalanced, with the latter seeming to have a lower load than the former.

Figure 12 Controllers' activities according to situations



There was a clear increase in the activities on the clusters during situation B, while those related to the flights drop significantly. This can be explained easily because STAR sent instructions to aircraft that are delegated by TC. The activity of the PC increased during situation B compared to situation A: the PCs needed to define the clusters, and then to prepare them for the TC by defining a strategy for resolving the conflicts. In contrast, the activity of the TC remained stable: the decrease of the TC's actions on the aircraft is compensated by the increase of the TC's activities linked to the management of CWS (e.g., delegation, modification). So, the conditions in situation B allow more time for managing problems efficiently.

In situation C, the different activities are unbalanced. The actions on aircraft increased compared to situation B, which indicates that the support system was used less, particularly the delegation function. This situation reveals an overload of the RC, whose activity level is higher than during situation A when the support tool was unavailable. Thus, in the context of an analysis of the activities on the system, situation C appears to be the least efficient.

7 Conclusions

In this article, we presented the AMANDA project. This project aims to evaluate the task delegation principle. This project is based on several studies applying the human–machine cooperation principle, especially dynamic task allocation, to air traffic control.

The assistance proposed to controllers helps to finalise their high-level decisions. From a strategy chosen by the controllers, the system defines satisfying sequence of actions and then selects one sequence in accordance with the controllers' preferences. Such assistance requires the introduction of new specific information, representing pieces of the decisions usually manipulated by controllers, but never practically expressed.

A first experiment allowed defining the effective contents of a CWS to be defined based on the controllers' COFOR, the allocation of functions between controllers and a new support tool that which integrates human strategies, and finally the modes of cooperation between the controllers and the tool. A second experiment was conducted to evaluate these principles. Analysing the controller activities confirms the preliminary results, namely, that situation B represents the best distribution of tasks between the PC and the TC.

In spite of a low number of controllers, we can conclude that the AMANDA V2 platform offers an interesting solution to air traffic controllers given the current increase in the amount of air traffic. Indeed, using AMANDA V2, the controllers were able to manage air traffic that was twice as intense as the existing traffic patterns. The task distribution judged the best requires the PC to create the clusters (the problems representation) and to define a problem-solving strategy. Then, the TC must evaluate the pertinence of the solution calculated by STAR, choosing either to delegate this problem, and its associated solution, to STAR or to maintain control.

Even though the results obtained from these experiments are globally positive, certain points must be improved. First, the support system interfaces were judged awkward to use by the air traffic controllers. Improving these interfaces is essential, in particular by decreasing the number of manipulations needed to define a strategy (directive). Second, in order to validate our results, an experiment must be carried out on a greater scale, with more controllers participating, so that the results can be analysed statistically and the biases of the system can be kept to a minimum. These modifications will be taken into account in the future experimental platform, AMANDA V3, in the collaboration with the CENA.

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