EVALUATION OF A COOPERATIVE AIR TRAFFIC MANAGEMENT MODEL USING PRINCIPLED NEGOTIATION BETWEEN INTELLIGENT AGENTS

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ABSTRACT

Air Traffic Management decisions affect the interests of a diverse group of organizations and individuals. Agents, including individual aircraft, airlines, and ground control centers, look for conflict-free options that meet their own interests without deprecating other agents’ operations. A cooperative structure for interactions of agents has been defined on the basis of Principled Negotiation. This method allows distributed decision-making for all users while providing a fair coordination through Air Traffic Management systems. The major interest of Principled Negotiation relies in its mutual gain approach to selection of options. Agents negotiate options with a traffic coordinator that ensures coordination of all users preferred operations while satisfying safety criteria. Thus, the model is flexible in responding to the needs and goals of agents, and it maintains safety. It provides users with different interests the freedom to optimize their operations, it includes Air Traffic Flow Management processes, and it certifies safe aircraft separations. A computer simulation dedicated to evaluating the benefits of such a cooperative structure is under development. The simulation provides trajectory-based traffic modeling with freedom of routing, communication, and negotiation modeling. It incorporates intelligent behavior modeling and incorporates airborne collision avoidance systems. First results show that Principled Negotiation is appropriate for coordination in a multi-agent/multi-interest system such as the Aircraft/Airspace System.

INTRODUCTION

The global Aircraft/Airspace System (AAS) is experiencing a continuing growth in air traffic that challenges current systems of Air Traffic Management (ATM) [1, 2]. Severe restrictions are imposed by Air Traffic Control (ATC) organizations in order to maintain safety. These restrictions prevent the aircraft from flying optimal routes, cost airlines millions of dollars, and cause delays that do not please passengers. The increasing air traffic levels demand more flexible airspace management that cannot be reached with imposed flight paths. As the complexity of the air traffic systems grows, it becomes more difficult to design an effective centralized control system. Moreover, airlines and aircraft are getting more and more aware of the real-time air traffic situation, so they can take part to the airspace management. Therefore a combination of on-board and ground-based systems is needed. The issue is how to get systems to play together.

Ground-based automation tools, such as the Center-TRACON Automation System (CTAS), are currently being developed [3]. By combining real-time trajectories prediction techniques, aircraft scheduling algorithms, and controller-CTAS interfaces, computer-generated advisories are provided to aid the en-route and terminal area controllers in efficiently managing arrival and departure traffic. The development of CTAS emphasizes the substantial progress in development of decision-making tools that decrease route constraints.

On a longer term, the Free Flight concept is being considered as a major component of future Air Traffic Management. It is meant to provide safe and efficient flight operations under Instrument Flight Rules, giving operators the freedom to select their path and speed in real time [4, 5]. Free Flight has been examined in a number of such distributed approaches. Among them, Steeb et al studied the air traffic process when coordinated by the aircraft themselves [6]. The prime goal was conflict avoidance rather than optimization of Free Flight operations. All these models are based on a

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competitive Free Flight environment, where conflicting objectives decrease the global efficiency. In high-density airspace, controllers might just switch off the Free Flight system and impose trajectories to provide safety, thereby losing the advantages of Free Flight.

Distributed Artificial Intelligence (DAI) provides a promising solution approach to the problem of controlling large-scale multi-agent systems. The idea is to decompose problems, allocating parts of the solution to intelligent agents. Davis and Smith examined the issue of distributed surveillance [7]. Distribution of the coordination or control function has been approached from a game-theoretic point of view by Levy and Rosenschein [8]. In these models, users have both increased capabilities and traffic management responsibilities. This situation requires complex communication interactions between users and traffic coordinators to avoid overlapping decision priorities.

An alternative approach is to consider a cooperative system based on negotiation. Green et al. evaluated a centralized Air Traffic Management system to enable user preferences [9, 10, 11]. With knowledge of users' capabilities and preferences, ground-based decision-making tools will be able to assist pilots to fly optimized routes. This cooperative system offers equitable compromises between flights with conflicting interests, but does not allow freely distributed optimization.

Stengel and Wangermann introduced Distributed Artificial Intelligence to provide users with the capabilities to optimize their own operations, while defining a cooperative system through negotiation for safe and fair interactions [12, 13, 14].

Proposed Approach

The Intelligent Aircraft/Airspace System (IAAS) is based on the following leading idea: Air Traffic Management systems should coordinate the traffic and leave the optimization to users. Principled Negotiation is used as a communication process between aircraft and traffic coordinators [15]. Aircraft are free to optimize their operations according to their own interests. Traffic coordinators insure fairness to all users and check global safety criteria.

This paper describes the concept in terms of the roles of user and ATM systems, and it explains the interactions due to the negotiation process. The principles, the current structure of the simulation, and its dynamic organization are presented. Examples of simulation evaluations are given, followed by concluding remarks.

COOPERATIVE MODEL

Developments in communication, navigation, surveillance, computation, aircraft performance, and airport design will make new operational structures possible. The development of a global Aeronautical Telecommunication Network (ATN), an "Internet in the sky" will enable cooperation between smart planes and smart ground control [16, 17]. With such a network, any kind of information will be both available to and provided by all agents of the Aircraft/Airspace System (AAS).

As technology develops, all the AAS agents will become increasingly capable and intelligent enough to cooperate. The Intelligent Aircraft/Airspace System (IAAS) has been defined to take into account these new capabilities. Its main features are:
- to absorb the increased demand for airspace while maintaining or improving safety,
- to make airlines more autonomous and more profitable, by considering a free-routing airspace environment,
- to organize cooperation between ground and airborne systems while managing the potential conflicts raised by overlapping new capabilities, and
- to deal with both unequipped and smart aircraft.

The IAAS is set up as a hierarchical structure (Fig. 1). At the top of the hierarchy, a central agency defines the overall requirements for air traffic; at the bottom are the individual aircraft. At intermediate levels are the traffic management agents: the terminal areas (TRACON), the sector and regional

![Figure 1. The IAAS Hierarchical Architecture.](image-url)

en-route control facilities (ARTCC), the airport and airline operators (AOC), which already cooperate with

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flow control and support aircraft in flight, and the meteorological forecasting centers, which provide information on local airspace. This architecture is built on the current one, an important issue for transition to any future system. The main differences reside in the role of each agent and in the interactions between them.

The IAAS should facilitate effective participation of each agent while providing clear lines of authority. For example, the traffic management agent whose airspace area includes the whole trajectory of an aircraft would be the adequate traffic management agent with which to cooperate. Conflict resolution or trajectories optimization could be processed while preventing overcapacities at any point (and any time) of the considered airspace area. Flow management and aircraft separation functions are combined in a single process.

In the open environment made possible by IAAS, all agents identify scenarios, assess the situation, and make decisions, but they have different interests and priorities when choosing how to respond to a particular situation. The IAAS should therefore satisfy as many diverse objectives as possible while satisfying constraints.

Agents in the IAAS

There are many actors within the IAAS. Four major classes of agents can be defined: the operator agent, the aircraft agent, the airport agent, and the traffic management agent.

The operator agents, as in the case of an Airline Operations Center (AOC), have to deal with a fleet of aircraft. Their role is to define a maximal profitable operating schedule according to information on the fleet status, weather, and traffic situation. Cooperation between other operators and the airport agents is used in the IAAS to improve the global Air Traffic Flow Management, by allowing arrival and departure slots negotiations.

The aircraft agents conduct real-time flight operations. With information on the nearby traffic situation, they plan their maneuvers for an optimized and safe trajectory. Negotiation with the traffic management agents is needed for acceptance of maneuvers, coordination, and arbitration in the IAAS.

The airport agents negotiate with operator agents for use of ground facilities, including runways, taxiways, and gates. If aircraft are delayed, airport agents revise plans for use of these facilities.

The traffic management agents (ARTCC, TRACON) monitor and project the traffic situation in order to identify potential conflicts. In the IAAS, traffic management agents first send conflict warnings. If the concerned aircraft agents are unable to negotiate a profitable conflict-avoidance maneuver, a traffic management agent acts as an arbitrator. The IAAS also enables traffic management agents to act as coordinators, thus, all aircraft are considered by the system. It lays the foundation for efficient mixed-fleet operations (unequipped and fully equipped aircraft), while providing additional efficiency benefits for users who invest in greater on-board capabilities. It may also provide a foundation to support other types of aircraft, such as rotorcraft and private planes. This coordination role would allow a smooth transition from present Air Traffic Control to IAAS Air Traffic Management.

Negotiation Process

To model the negotiating behavior of an intelligent agent, a set of internal functions were defined according to a hierarchy of thought processes:
- Declarative functions are the conscious and pre-conscious processes which typically involve decision-making (Goal Setting, Action Planning, Scenario Identification)
- Procedural functions are the sub-conscious procedures equivalent to a set of internal capabilities to integrate information (Skill Learning, Knowledge Acquisition)
- Reflexive functions are elementary actions which involve interfacing with the outside

Thus, each intelligent agent does more than executing the instructions of a superior entity in the IAAS hierarchy. Cooperation between intelligent agents is made possible through both transfer of information and negotiation.

Principled Negotiation

All agents can contribute to the IAAS through Principled Negotiation, a method to produce agreements that are beneficial to all parties in negotiation. Principled Negotiation exploits the fact that two parties in negotiation have common interests in reaching an agreement. Each agent should consider both its own and other agents' interests, identifying those that are common and those that are separate.
For instance, “No Airspace Congestion” could be considered as a common interest, while “Reduced Fuel Consumption” is of primary interest to the individual airplane.

Principled Negotiation minimizes the risk of fruitless negotiation by influencing agents to search for options for mutual gain. Thus an agent would propose changes to any aspects of its flight if it believes that these options would improve its own operational performances and that, at a minimum, other agents would not be adversely affected.

Finally, options are more easily agreed upon if the parties use common objective criteria for assessing them.

According to these rules, agent interactions governed by Principled Negotiation ensure cooperation while giving freedom to optimize operations. The method could be summarized through an iterative algorithm (Fig. 2):

1. An initial master plan is formulated, specifying the actions of each agent.
2. Agents repeatedly search for better options that provide mutual gain. When found, the best option is proposed.
3. The other agents evaluate the option according to their own interests.
4. The option is accepted or rejected. If rejected, the reasons of rejection could be used as extra information to improve search.

<table>
<thead>
<tr>
<th>Negotiation Steps</th>
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</thead>
<tbody>
<tr>
<td>1. Initial Master Plan</td>
</tr>
<tr>
<td>2. Options for Mutual Gain</td>
</tr>
<tr>
<td>3. Options Assessment</td>
</tr>
<tr>
<td>4. Response</td>
</tr>
</tbody>
</table>

Figure 2. Steps in Principled Negotiation.

Negotiating Behaviors

Agents use different methods for assessing options and display different negotiating behavior. Some agents display maximizing behavior in negotiating situations, while others display satisficing behavior [12]. Agents such as aircraft and airlines operators generally attempt to maximize some utility function. A maximizer tries to ensure that any agreed-upon option provides increased utility compared to the existing plan; when given a choice, it chooses the option with maximum utility and mutual gain. Traffic management agents are typically satisficers. A satisficer is an agent that assesses options presented to it by operating agents; it accepts an option if certain criteria are within defined bounds.

If two maximizers are in negotiation (Fig. 3), any option proposed must be in the feasible set of both agents. New options provide a higher utility to the agent that initiated the negotiation. At a minimum, these new proposals should not knowingly make things worse for other agents in negotiation. If the other agents’ operations improve, it’s all the better. Nevertheless, if the two maximizers are in conflict, the maximum utility option may not be possible for both, and arbitration may be needed.

If a maximizer is negotiating with a satisficer (Fig. 3), it must propose options that lie within the satisficer’s satisfactory set for acceptance. The satisficer shows no concern for maximizing individual or global operating criteria; it does, however, assure safe, conflict-free operation of the global system. In the negotiation process, a satisficing agent could suggest an alternative option that it believes will improve a maximizing agent’s plan; however, the maximizer would not be obligated to accept the alternative proposition.

Data Exchanged

Coordination implies negotiation between a maximizer (aircraft or airline operator) and a satisficer (traffic management center). The airline agents first negotiate for departure and arrival slots with airport agents. This is similar to the present flight plan process. In the IAAS, slots are assumed to be negotiated for maximal flexibility. During flight, an

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aircraft may need to re-negotiate the trajectory path and its arrival slot because of delays due to traffic congestion, meteorological hazards, and conflict-avoidance maneuvers.

During trajectory optimization, identification data, present position, flight path as a time sequence of waypoints, real-time state updates, and proposed operations are transmitted to the appropriate traffic coordinator agent. The proposed operation data are based on maneuver sequences, which are represented by four variables. The first determines the type of maneuver (Turn, Climb, or Acceleration). For each maneuver, a start time, a target value, and a maneuver rate are specified as three numerical variables. This simple format provides rather precise information while minimizing the amount of data to be communicated. Negotiation based on these maneuver sequences enables agents to perform accurate traffic prediction for better coordination (Table 1).

<table>
<thead>
<tr>
<th>Time</th>
<th>Aircraft Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>680.0</td>
<td>Predict conflict with aircraft below</td>
</tr>
<tr>
<td>685.0</td>
<td>Propose avoidance maneuver to TrMA</td>
</tr>
<tr>
<td></td>
<td>C 686.0 50.0 5.0</td>
</tr>
<tr>
<td></td>
<td>C 705.0 0.0 -5.0</td>
</tr>
<tr>
<td>686.0</td>
<td>Proposition evaluated and accepted</td>
</tr>
<tr>
<td></td>
<td>Conflict being avoided</td>
</tr>
<tr>
<td>710.0</td>
<td>Cruise / Will not meet next waypoint</td>
</tr>
<tr>
<td>715.0</td>
<td>Propose optimization maneuver</td>
</tr>
<tr>
<td></td>
<td>A 716.0 440.04 0.38</td>
</tr>
<tr>
<td>716.0</td>
<td>Proposition evaluated and accepted</td>
</tr>
<tr>
<td>720.0</td>
<td>Cruise / Will meet next waypoint</td>
</tr>
<tr>
<td></td>
<td>Cruise / Will meet next waypoint</td>
</tr>
</tbody>
</table>

Table 1. An Example of the Proposition Process.

**INTELLIGENT AIRCRAFT/AIRSPACE SYSTEM SIMULATOR**

Adequate agent-oriented methodology and modeling techniques are appropriate to implement multi-agent systems [18]. Autonomy and cooperation skills are used to perform some intelligent behaviors of the IAAS agents. In our simulation of the IAAS, called IAAS-SIM++, agents have been implemented with CLIPS, an expert-system shell developed at NASA Johnson Space Center [19]. CLIPS provides object-oriented, procedural, and rule-based programming facilities. An object-oriented environment is used to define a class hierarchy based on the negotiating behavior. Rule and data bases are used to govern the negotiation through a deductive process.

CLIPS has been embedded in a C++ program (Fig. 4). The C++ program produces the graphical display and controls the execution. The structure is based on Event Scheduling. While the simulation is running, events are posted to an agenda, where they are classified according to the time they should happen. The agenda executes these events at the proper time. Priorities also are used to execute events in a particular order. When an event is executed, a message handler is sent to the concerned agent, which reacts by executing an internal function. Thus, loops on all agents are avoided.

![Image of the IAAS-SIM++ Organization](image)

The fully object-oriented simulation could be ported to a multiprocessor environment. The interactions between the C++ program and the expert-system provided by CLIPS offer an appropriate foundation for the modeling of intelligent behavior by agents as well as the modeling of communication and negotiation between agents.

Because the IAAS is a global system taking into account many future capabilities, these should be part of the simulation. Trajectory optimization algorithms, conflict detection functions, and traffic situation evaluation are all implemented. This global approach provides a general vision on the performance of the model, as indicated in Fig. 5.

**Trajectory Optimization**

The trajectory optimization algorithms, developed by Erzberger et al, are in wide use [20, 21]. They are based on the specific energy of an aircraft,
depending on altitude and velocity. The optimal trajectory is assumed to take a three-segment form: a climb with monotonically increasing energy, a cruise portion at constant energy, and a descent at monotonically decreasing energy. This algorithm is used to determine the initial flight plan and to revise the trajectory if required by conflict-avoidance maneuvers or meteorological constraints.

Hybrid Extended Kalman Filters

Aircraft should be able to assess the immediate traffic situation and to predict any impending conflicts in the near future. This airborne traffic-sensing capability provides redundancy to the IAAS, an extra alerting system that completes the traffic management agents' conflict-warning function. The on-board TCAS-like system incorporates both accurate estimation of state data and information about planned maneuvers. With these data, Extended Kalman Filters (EKF) project an aircraft's future trajectory. EKF also is used by the traffic management agent to predict traffic situation on a long-term scale. This function enables traffic management agents to inform aircraft of potential conflicts that cannot be predicted by aircraft with only TCAS-like measurements for look-ahead times up to thirty minutes.

Conflict Resolution

When aircraft are aware of possible conflicts, they should perform an evasion maneuver. These maneuvers are either determined by the aircraft itself, or imposed by the traffic coordinator. The TCAS-like advisories defined on-board are usually based on vertical separation. Climb maneuvers are performed by aircraft involved in a conflict in order them to be vertically separated by 20FL. Nevertheless in some other situations, aircraft perform more complex maneuvers. For instance, in a busy Terminal Area, a tight landing sequence could require aircraft to be closely separated. A decrease in both speed and climb rate is enough to enable safe separations while sequencing aircraft for high rate landings. If not enough, traffic management agent should send orders to the involved aircraft, such as to put the aircraft on hold.

Multi-Attribute Utility Theory

A maximizer checks to see if a proposed option has an increased utility compared to the present plan. The utility of an option may be difficult to quantify, as the agent may be interested in many different attributes of the option. For instance, an aircraft agent assessing a trajectory change considers the effect of arrival time, fuel consumption, safety, direct operating costs, or passenger comfort. As the situation is dynamic, the relative weight that a maximizer attaches to these attributes may change as well. An on-time aircraft may weight fuel usage heavily, while an aircraft suffering from delays may place higher weight on minimizing flight time. This behavior can be represented using Multi-Attribute Utility Theory. Each agent generates a set of options. For each generated option, the values of the different attributes are assessed, and they are combined through a weighting matrix to calculate the option's utility.

Decision Tree

A satisficer (a traffic management agent) has to handle multiple proposals, so the method of assessment must be quick and accurate. Traffic management agents would receive many proposals from subordinate agents for changes to trajectory plans, and would also have to detect conflicts and hazardous situations rapidly. A traffic management agent would therefore need rapid assessment of present and future traffic situations in order to make decisions accordingly.

When a satisficer assesses a traffic situation, it has to classify the situation as safe or unsafe. Decision trees, which perform a sequence of tests for various factors of a situation, are well suited to classification problems. The outcome of these tests determines the decision taken. An oblique decision tree (OCT) is used to test linear combinations of attributes in IAAS-SIM++ [22].

General Algorithm

The process of enabling user preferences within the IAAS may be divided in several steps.
representing key user/traffic management agent interactions. First, each aircraft specifies its flight plan, within an initial master plan. Then, on a one-second time interval, situation parameters are updated. All agents assess the situation according to their capabilities, and utility estimation and conflict detection prepare the mutual gain optimization. Finally a negotiation action is executed if at least one agent requires a new plan, and new trajectories are then computed.

**SCENARIO PARAMETERS FOR COMPLEX-Traffic Simulations**

Real air traffic is composed of individual aircraft with different capabilities and diverse interests. Every day, these individual aircraft face hazardous uncertainties and structural constraints.

In an initial test of the IAAS-SIM++, some forty five aircraft are simulated, flying in the Denver International Airport airspace (Fig. 6). Data on the traffic over this area were generated from the OAG Desktop Guide [23]. A set of parameters can be accessed to set and modify this general simulation scenario in order to include difficulties. Thus, the cooperative IAAS model can be confronted with different critical situations that are quite common in reality. Uncertainties and constraints can be introduced in the simulation in order to define a more complex scenario. By allowing negotiations between these simulated aircraft (the “Negotiations” button), comparisons can be drawn between the usual competitive Free Flight concept and the cooperative IAAS approach (Fig. 7). This provides a reference model from which benefits can be observed.

![Figure 7. The IAAS-SIM++ Scenario Input Form.](image.png)

**Meteorological conditions**

An important issue is to observe how the system would react to changing conditions of the airspace. One major cause of delay is due to meteorological conditions. A model to take into account wind effect (the “Winds Aloft” button) is included in the simulation tool. Changing wind direction and velocity have an effect on the ability of aircraft to fly their planned optimal routes. Aircraft must adapt to this situation by taking into account the wind in their route optimization and by negotiating new trajectories.

The major problem relies in avoiding “Tough Weather Areas”, such as storms. The fast changing nature of these uncertainties demand a real-time adaptation. The presence of such areas in the airspace makes aircraft change their path, and traffic concentrates in safe airspace. This unpredicted high-density traffic creates severe conditions [24].

**Diversity of Simulated Users**

All users should benefit from the IAAS, thanks to the search of mutual gain and to the arbitration role of the traffic management agents. To provide the system with more realistic traffic, simulated users should not be uniform.

The simulation deals with models of different types of commercial airplanes (B727, B737, B767 and A310). At this point in simulation development, this only affects route optimization. More severe differences can be included to evaluate the fairness of the system.

Unequipped, partially equipped, or fully equipped are implemented to evaluate the coordination role with aircraft of different capabilities (the “Diverse Aircraft Type” button). Private planes, helicopters, or other types of aircraft should be considered as well. They might not use the same part of the airspace but...
could use the same runway approach and departure space, runways, and other airport facilities.

Users are characterized by more than differences in technical capabilities: they also have different interests. A set of interest factors is used to define each user's own utility function. "Airline Policy" and "Pilot Aggressiveness" are the two criteria that are currently considered. Both will be included in each aircraft utility function through Multi-Attribute Utility Theory. Airline Policy can influence fuel consumption or the total time of flight through economical profit interest. Pilot Aggressiveness represents the acceptance of pilots to certain options: how close pilots are willing to fly to storm cells is an illustrative example. This parameter is modeled by a stochastic function based on surveys among pilots [24].

Other Capabilities

Other characteristics of air transportation can be added in a scenario. "Restricted Area" is used to define real structural constraints: bottlenecks, or airways can be created by imposing large restricted areas. Accidental uncertainties, such as the loss of a runway in an airport or the loss of on-board equipment, are considered as well, in order to evaluate the effect of this type of uncertainties.

All these capabilities provide a means to perform simulations with complex traffic situations. The models are abstractions of complex air traffic situations, allowing many IAAS scenarios to be tested.

**Preliminary Results**

Improved safety and more efficient performance are the major benefits required for future ATM systems. During the IAAS-SIM++ simulation, three safety quantities are evaluated: the Number of Incidents (an Incident occurs when two aircraft have a Lateral Separation inferior to three nautical miles and an Elevation Separation inferior to five Flight Levels), the Minimal Lateral Separation, and the Minimal Elevation Separation. Four performance metrics are calculated: the Total Fuel Consumption, the Number of Aircraft Delayed, the Mean Delay, and the Percentage of Accepted Proposals during negotiation. These data offer a global analyze of the general benefits of the system. We collected a set of values of these data when simulations were run. The mean value and the standard deviation obtained from these data sets helped to determine a pertinent number of simulations to draw some conclusions (Fig. 8).

![Figure 8. Histograms and Associated Normal Distributions for a Simulation of Twenty Initial-Condition Sets.](image)

The scenario defined for these simulations is critical from a safety point of view. All the aircraft are fully-equipped so they can optimize their operations, be responsible for the safe separations, and be able to negotiate with the traffic management coordinators. During negotiation, these coordinators assess users' proposals on the only criteria of safety: if the proposed option is safe at current time of evaluation, then it is accepted. The arbitration role of these coordinators is not set up: there is no redundancy on conflict detection. Winds also are taken into account.

On the basis of twenty simulations, no Incident occurred. All the conflicts are avoided thanks to the TCAS-like on-board conflict detection system, and the avoidance maneuvers that are planned by the aircraft and negotiated with the coordinators. Both the Minimal Lateral and Elevation Separations are superior to the separations retained to define an Incident. On cruise, the Lateral and Elevation Separations observed correspond to safe separations: typically 35NM and 20FL, but, the minimal values were recorded when aircraft were in Terminal Airspace, where traffic is usually busy (Table 2). The average value of 3.8NM Lateral Separation (at same FL, before the final descent) actually corresponds to a needed separation between two aircraft that are scheduled to land within a two min interval (at a speed of 250kts). Aircraft are therefore capable of inventing optimized options which are adapted to both flow scheduling constraints and safety criteria.
Table 2. Worst-Case Separations for a Simulation of Twenty Initial-Condition Sets.

<table>
<thead>
<tr>
<th>Incidents</th>
<th>Average on 20 Simu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal Lateral Separation</td>
<td>3.03NM occurring at 10FL</td>
</tr>
<tr>
<td>Minimal Elevation Separation</td>
<td>0.27FL occurring at 3.87NM</td>
</tr>
<tr>
<td>Simu Time</td>
<td>3600s</td>
</tr>
</tbody>
</table>

An average of three aircraft per simulation are delayed (out of forty five). The Mean Delay is about two minutes (Table 3). Even though aircraft are affected by conflict avoidance procedures and winds aloft, they are capable of flying very close to the initially planned optimized operations.

Table 3. Performance Criteria for a Simulation of Twenty Initial-Condition Sets.

<table>
<thead>
<tr>
<th>Delays</th>
<th>Mean Delay</th>
<th>Proposals Acceptance Rate</th>
<th>Simu Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100% 130s 379.9</td>
<td>3600s</td>
</tr>
</tbody>
</table>

All users’ proposals are accepted by the traffic management agents in this example (Table 3). This can be explained by the mutual gain requirement when users look for new options: one of the common interest of all users is to fly in a conflict-free airspace. Aircraft actually manage to take this common interest into account; therefore traffic management agents, which check the present safety of these proposals, approve the options. During first simulations (when all parameters were not precisely set up), traffic management agents sometimes refused a proposal. It was due to aircraft sending options to optimize their performance operations while being in a conflict situation. The responsible traffic management agent gave no acceptance to these options; in fact, they should have ordered some conflict avoidance maneuver to the incriminated aircraft as well (a function that is not implemented yet). Obviously, a more complex procedure for proposal assessment can be included for future simulations.

Results for this scenario show the ability of the system to coordinate the flights of several aircraft in a free-routing airspace environment, where aircraft are free to optimize, and when no arbitration is insured. More complex scenarios will have to be performed, and comparisons between simulations with and without “Negotiations” button will be drawn (Fig. 17).

**CONCLUSION**

The Intelligent Aircraft/Airspace System concept has the potential of enabling users to optimize their operations while providing coordination through air traffic management systems. Thus operating efficiency improves because of greater freedom for airline operators and aircraft. Data exchanged in the cooperation process enables the integration of users and Air Traffic Management capabilities for a fair coordination and enhanced safety. The current evaluation is based on a system with no traffic management arbitration. Nevertheless, the users are able to integrate the traffic constraints in their trajectory optimization to avoid conflicts. The redundancy due to the arbitration of the coordinating agent provides a safer environment for users and insures users of different capabilities to benefit from the system. Further simulations will be conducted on different scenarios for a better performance evaluation.

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