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Air traffic knowledge management policy

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Abstract

A new air traffic knowledge management system is vitally important for the safety and efficiency of future air travel. It can be accomplished by developing a new-generation integrated operational decision support for pilots and controllers. At present the knowledge for decision making is only available when the latter parties share it and negotiate it in real-time. A new policy is required with a new management system and an automated planning of conflict-free air space–time allocation accomplished by an agent-based architecture of a global network of integrated operational decision support systems for airports, airlines and air traffic control. This aims at acquiring and monitoring a flow of air space–time knowledge-and-data structures of conflict-free and optimised flights given the available resources, and ensuring their long-term efficiency by an agent-based planning of flight-plan alterations off-line before signs of air space–time conflicts can develop in real-time. The Agents managing parallel knowledge acquisition and reasoning processes allocate air space–time resources according to the technical capabilities of aircraft in response to flight-plan clearance requests. They ensure decision support for efficient flights and use of air space–time, and conflict-free planning for air traffic management.

Keywords: Decision support; Knowledge management; Knowledge acquisition and reasoning; Concept learning; Agent-based technology

1. Calls for changes

The current system of air traffic management is experiencing problems with coping with the estimated and inevitable increase of air traffic. Airports report with an irritating frequency flights which have been delayed.

As an air travel passenger I have experienced delays of flights caused by the deficiencies of the air traffic management. The most shocking experience was when I was travelling in the spring of 1998. A number of flights were cancelled and more were delayed. As a result a great number of passengers were waiting several hours without having any assurance when or whether there would be sufficient number of flights to take them to their planned destinations within a reasonable timescale. I waited patiently for several hours assuming that the airlines and airports officers knew their responsibilities towards their passengers and would

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take care of us all. The latter belief created during the golden era of glamorous air travel happens to be out of date. I had a connection to catch at New York and I had to convince the airline officer before being allowed to board a plane that would take me there in time.

Another organisational deficiency has been made apparent to me as a passenger at a very busy international airport in the summer of 2000. Airport and airline officers do not always know the correct numbers of the gates from which flights leave and are unable to help the anxious and often hurried travelers who ask them. This irritating anomaly makes one wonder if the scheduling of gates and planes is still done manually. The airport officers were all carrying written notes which suggest that this was the case. Apparently they had different notes of the gate-number for a certain flight. To add to the story, all of them were sure that they had the correct information despite the fact that everything was most chaotic. The monitors were giving information that the flight was scheduled to leave from a certain gate but this turned out not to have been the correct one. It is most important that this situation be rectified. If the airport system cannot update its schedules electronically how can we expect the airport officers to inform the passengers correctly about the gates to which they should report and the flights to avoid delays?

The above practice is extremely inefficient. Incidents and delays of this nature are upsetting to passengers and not good for the reputation of the airports and airlines. They can be and should be avoided. In a complex system such as air traffic management we should not blame the air traffic control for all the delays of flights. Delays of flights can be caused not only by the current air traffic control operations but also by bad scheduling of airports' and airlines' operations.

It seems that the air travel is losing not only its glamour but also its reliability. 'The truth about the Air Traffic Control' revealed us by Perry [17] is that the ATC systems all over the world and particularly in the US domestic airspace rapidly lose their reliability for three main reasons: ageing equipment, old software, and maintenance problems. The airline operators lose billions of dollars annually because of delays of flights.

New strategies for increasing the capacity of the airspace are considered by the industry. They are reduction of the separation requirements between flight-plans, introducing of a flexible, more efficient, airspace track structure over the North Atlantic and air traffic routes in domestic airspace, and pilots being able to plan the most efficient route referred to as "free-flights". The North Atlantic Simulation Model [13,14,19] is designed to explore the strategies for increasing the airspace capacity. Steps have already been taken to modernise the existing air traffic management system. New Optimisation Approaches to Air Traffic Flow Management [15] have been considered by the European Organisation for the Safety of Air Navigation EUROCONTROL. The US National Airspace Board plans to move towards "free flights" (http://www.faa.gov/freeflight) by various phases. Phase 1 is expected to end in December 2002 to be followed by Phase 2 introducing incrementally new capabilities from 2003 to 2005.

As yet the industry does not consider introducing a new strategy for improving the management of the air traffic by setting up a new system of managing knowledge and airspace. In order to recover its former efficiency the industry has to introduce fundamental innovations and inter-organisational improvements.

1.1. Airspace and knowledge management

This paper draws attention to the limitations of the current system of manual air space design and of the management of air traffic and knowledge. These are the factors which make a new air traffic knowledge management policy necessary. This aims at developing the air traffic management system and overcoming its deficiencies. To do this requires a new way of coordination and adequate sharing of air traffic knowledge which is managed at present by the three parties involved in the air traffic industry namely, the airports, the airlines and the air traffic control centres. This paper introduces the policy's innovations which will reshape and develop the present system. It discusses the design and technical effects of integrated operational decision support (IODS) systems [3,4], and the benefits for the management of air traffic, airspace, and knowledge that this will bring.

In the current practice, the air traffic control centres are in charge of issuing clearances of flight-plans in response to flight-plan requests and also their conflict-resolution alterations in response to conflicts predicted by the existing decision support in use for this. The conflict-resolutions of flight-plans remain manual. The air traffic controllers have sufficient knowledge about the available and occupied airspace provided by the present merely conflict-prediction systems, while the pilots have sufficient knowledge about the technical characteristics of the aircraft and its capabilities under the current loading. Neither side has enough knowledge to propose feasible and efficient flight-plan clearances without negotiating them with each other. In the limited time available to make the vital decisions, the controllers and pilots have to pool the essential information each of them possesses in order to negotiate and agree technically feasible and efficient alteration of flight-plans before the controllers can finally issue the clearance. In this manual practice, the negotiating of clearances and of resolutions of en-route conflicts requires more time than they should. This time they have to spend in exchanging information in order to make vital decisions greatly adds to the workload of the controllers and is a risk factor for the safety and the efficiency of the air travel and the use of airspace capacity.

This practice is also responsible for separating the two distinct processes in the current air traffic control operations, that of conflict-prediction and that of conflict-resolution. While conflicts are predicted by the existing tools, conflict-resolution processes rely on the above exchange of vital knowledge between pilots and controllers. The manual conflict-resolution requires a negotiation of the disparate safety and economical concerns in real-time. The airline operators seek to ensure the greatest efficiency of flight-plans according to the technical capabilities of aircraft under the current loading, while the concerns of the controllers are with the safe separation of flight-paths of aircraft and with the efficient use of airspace. The very demanding job of air traffic controllers, who carry out on-line conflict-resolutions, is becoming more difficult as air traffic increases.

The main factors, which make a new policy for air traffic and knowledge management necessary, are the increasing air traffic and the limited airspace capacity which the current manual management system provides for it. The air traffic control operations must be done more quickly and with the greatest possible efficiency. To do this the vital decision-making processes must be speeded up. It is suggested that the air traffic industry give major priority to improving management of knowledge by introducing an automated IODS for pilots and controllers.

This proposed air traffic knowledge management policy provides a way of ensuring the safety and economic concerns of airlines and air traffic control and management. It aims at resolving inter-organisation problems, and ensuring adequate sharing of knowledge between air traffic controller centres and airlines via a global network of IODS systems. The policy's IODS provides a way of managing the knowledge that supports an automated air space–time design and conflict-free planning for air traffic. Such a policy provides a way of increasing the capacity of the airspace available for air traffic by ensuring a global planning of conflict-free air space–time use.

Whicher [20] predicts that the European ATC System will reach its capacity limit by 2003. PHARE program [16] involves the European EUROCONTROL Agency and Member States, and considers new air traffic concepts and decision support tools needed to handle more traffic. A new decision support tool such as the Highly Integrated Problem Solver (HIPS) [1] was developed under the PHARE program [10–12]. The Oceanic HIPS development [2,18] was undertaken by the Research and Development Directorate, UK NATS supported by the European Experimental Centre EUROCONTROL (EEC) Bretigny. Both versions of HIPS aim to provide more complete decision support information and to display air traffic information in an effective way to support the conflict-resolution undertaken by the controllers. HIPS provides a graphical editor of the flight trajectory of various aircraft, and also the diagrams for their performance. It deals with the hard resource constraints in facilitating the controllers' resolving of conflicts by manipulating an aircraft trajectory to avoid the 'no-go' zones indicated by the graphical trajectory editor.

HIPS aims to speed up vital decision-making processes. It relies on the experience and the judgment of the controllers to use the provided diagrams of aircraft performance characteristics to improve the efficiency of the trajectories of various aircraft. It also relies on exchange of knowledge between pilots and controllers concerning the current loading of aircraft. As yet it does not deal with an automated optimisation of the efficiencies of flights and air space–time use, though if it is further developed, it must be expected to do this.

Given the increased air traffic and the limits of the Air Space–Time (AST) resources the best that can be hoped is to make the most efficient use of them. This can be accomplished by an implementation of the new policy of managing airspace and knowledge via a global network of integrated operational decision support systems for airlines, airports and air traffic control. This policy draws attention to the importance of the conflict-free planning for air traffic. It can be accomplished by an automated airspace design, and monitoring and update of allocation of air space–time for keeping flights conflict-free in the long term with the fewest ATC interventions in real-time. It shows how an automated design of air space–time use can be accomplished by concept-learning acquiring and updating hierarchical air space–time knowledge-and-data structures for conflict-free flights and for ensuring their long term efficiency within the available resources. It draws attention to the importance of a new knowledge management to support an automated allocation of air space–time and ensuring of its conflict-free use by monitoring trajectory predictions of flight-plans and automated planning of their alterations off-line before a predicted conflict can develop in real-time. It brings this about.

It also brings about an IODS which will tell the controllers and pilots if "free-flight" is possible. If it is, the pilot goes ahead. If the IODS tells him that "free-flight" is not possible he must abandon his original plan. But the IODS systems will monitor and plan conflict-free air space–time allocation and will inform him about the available resources and alternative options for his flight to make it as close as possible to what he originally intended to do, as far, that is, as safety permits and efficiency suggests. It would also add to the efficiency of airspace management by Air Traffic Control centres and enable them to give the best assistance to the airline operators and their pilots. It would enable the pilots and the controllers to plan and keep to the best possible flights.

1.2. Innovations and benefits

The policy puts forward innovations which will reshape the air traffic management system and overcome its current limitations. First, it aims at overcoming the time-consuming need for essential information to be exchanged by air traffic controllers and pilots. This need can be obviated by introducing an IODS for them. This will improve the sharing of knowledge between all parties involved in the air traffic industry. Secondly, it puts forward an automated conflict-free planning of air traffic. It is intended to replace the current practice of manual airspace design and the current lack of planning of airspace use. This requires an integrated automation of conflict-prediction and conflict-resolution processes. This obviates the need of manual allocation of air space–time resources according to the technical capabilities of aircraft, and exchange of knowledge for decision making.

The air traffic management needs an advanced air space–time management and this policy provides this. The automated integration of conflict-prediction and conflict-resolution processes is needed if the efficiency of the use of airspace, of flights, and of air traffic control and management operations is to be improved.

The air traffic industry is in urgent need of a global network of new-generation IODS systems for airlines and air traffic control and management. It will ensure the efficient flight-plans and their conflict-free air space–time use before the aircraft take off from airports and keep them conflict-free and most efficient in the long term with the fewest ATC intervention in real-time. The policy's agent-technology of IODS systems delivers a way of achieving this.

Thus this policy proposes a build-up of main integrated components of an agent-based architecture of future IODS systems. It puts forward an advanced AST Management supported by an automated conflict-free planning for air traffic, and agent-technology of generation of decision support knowledge. It allocates AST resources efficiently according to the technical capabilities of aircraft and supports their conflict-free use in the long term, and thus also supports a new generation IODS for pilots and controllers.

The policy's IODS for pilots and controllers will reduce the ATC conflict-resolution interventions in real-time. It will ease the workload of controllers. The negotiation time between pilots and controllers will be obviated. There will be speedier flight-plan clearances. The better planning of the use of AST resources will increase the available capacity of the airspace and thus it will accommodate more traffic. The delays of flights caused by the present lack of a global planning of air space–time use will be obviated. The conflict-free planning for air traffic will enable the aircraft to keep to the time tables, and thus save a good deal of money to the airline industry. There will be also reduction of costs of flights by the optimisation of flight-plans within the resources available. Thus this policy will increase the efficiency of air travel and flying safety and will meet the increased demand for future air travel.

2. The air traffic knowledge

The new generation IODS systems integrate the management of the domain knowledge which at present the air traffic controllers and the airline operators have to share. Fig. 1 presents the integration of knowledge models within the future IODS systems for air traffic management.

The conflict resolution planning [3–6] in Fig. 1 deals with sets of fight-paths of en-route aircraft already being active in the air and with sequences of requests for clearances of flight-plans of other aircraft. With the aircraft already active in the air we associate a set of flight-plans **P**:

$$\mathbf{P} = \{p_k \,|\, p_k = (p_{k,1}, p_{k,2}, \ldots, p_{k,m_k})\}, \tag{1}$$

where $k = 1, 2, \ldots, n$; $n, m_k \in \mathbb{N}$.

With the aircraft requesting clearances we associate a set of flight-plan requests **Q**:

$$\mathbf{Q} = \{r_i \,|\, r_i = (r_{i,1}, r_{i,2}, \ldots, r_{i,j-1}, r_{i,j}, r_{i,j+1}, \ldots, r_{i,m'_i})\}, \tag{2}$$

where $i = 1, 2, \ldots, n'$; $n', m'_i \in \mathbb{N}$.

A flight-plan r_i requested for clearance consists of four-dimensional segments $r_{i,j}$, where $j = 1, 2, \ldots, m'_i$; $i, m'_i \in \mathbb{N}$. A feasible state r'_i of a flight-plan r_i is determined by feasible states of segments $r'_{i,j}$, where $j = 1, 2, \ldots, m'_i$; $i, m'_i \in \mathbb{N}$, which satisfy the integrity constraints of the flight-plan r'_i.

2.1. Constraints

The feasible states of the segments $r'_{i,j}$, where $j = 1, 2, \ldots, m'_i$; $i, m'_i \in \mathbb{N}$, satisfy the technical constraints of the aircraft associated with the flight-plan and the AST constraints.

Possible feasible states of a segment $r'_{i,j}$, where $j = 1, 2, \ldots, m'_i$; $i, m'_i \in \mathbb{N}$, of flight-plan r'_i comprise a set $R_{i,j}$:

$$\mathbf{R_{i,j}} = \{r'_{i,j} \,|\, \zeta(r'_{i,j}) \wedge \eta(r'_{i,j}, A_i)\}, \tag{3}$$

where

- the property $\zeta(r'_{i,j})$ is the state of the segment $r'_{i,j}$ which satisfies the AST constraints;
- the property $\eta(r'_{i,j}, A_i)$ is the state of the segment $r'_{i,j}$ which satisfies the technical feasibility constraints with respect to the performance capabilities of aircraft (A_i) originating the clearance request for flight-plan r_i;
- the A_i is an identification set of a particular aircraft allocated to the flight-plan r_i.

The AST constraints are determined by the following factors: recent weather forecasts, already occupied or reserved AST, and the separation requirements between flight-paths. There are three hierarchical levels of AST properties in the following order of priority:

- the property $\zeta'(r'_{i,j}, M_t)$ which is the AST period of a state of a flight-plan segment ($r'_{i,j}$, where $j = 1, 2, \ldots, m'_i$; $i, m'_i \in \mathbb{N}$) belonging to an overall available air space–time determined by the current weather and meteorological data M_t;

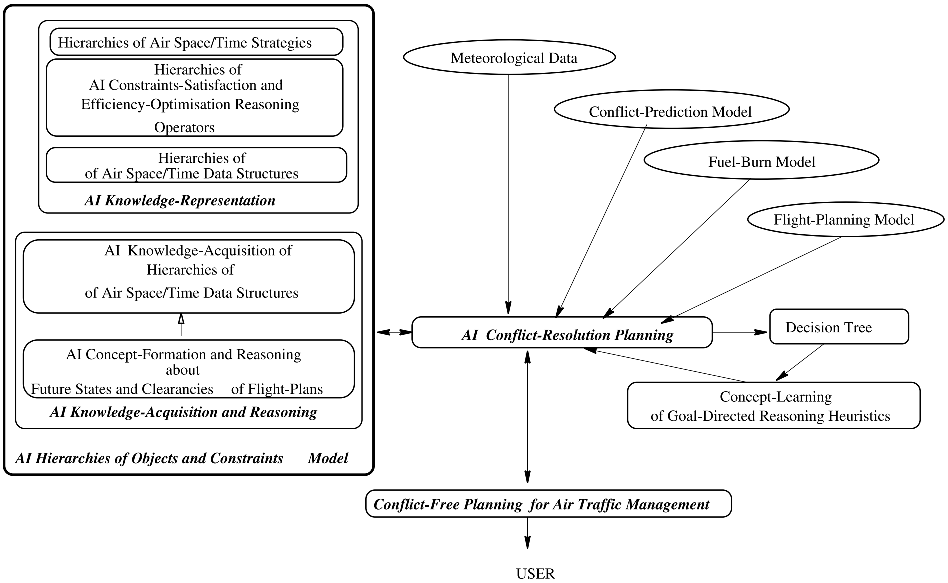

Fig. 1. Integration.

- the property $\zeta''(r'_{i,j}, \mathbf{P})$ which is the AST period of a state of a flight-plan segment ($r'_{i,j}$, where $j = 1, 2, \ldots, m'_i$, $i, m'_i \in \mathbb{N}$) which does not belong to occupied or reserved AST by other flight-plans belonging to the set $\mathbf{P}$;
- the property $\zeta'''(r'_{i,j}, S_r)$ which is the AST period of a state of a flight-plan segment ($r'_{i,j}$, where $j = 1, 2, \ldots, m'_i$, $i, m'_i \in \mathbb{N}$) which satisfies the separation requirements S_r between the flights:

$$\zeta(r'_{i,j}) = \zeta'(r'_{i,j}, M_t)_t \wedge (\zeta''(r'_{i,j}, P) \wedge \zeta'''(r'_{i,j}, S_r)), \quad (4)$$

where $j = 1, 2, \ldots, m'_i$, $i, m'_i \in \mathbb{N}$.

The $\zeta(r'_{i,j})$ is a logical function from properties $\zeta'(r'_{i,j}, M_t)$, $\zeta''(r'_{i,j}, \mathbf{P})$ and $\zeta'''(r'_{i,j}, S_r)$. These properties can take either value 'true', identified by 1, or value 'false', identified by value 0.

In conclusion the state of a flight-plan segment $r'_{i,j}$, where $j = 1, 2, \ldots, m'_i$; $i, m'_i \in \mathbb{N}$, can occupy an AST period which first belongs to an overall available air space–time determined by the current weather prognoses ($\zeta'(r'_{i,j}, M_t) = 1$), which secondly does not belong to occupied or reserved AST by other flight-plans ($\zeta''(r'_{i,j}, P) = 1$), and which thirdly satisfies the separation requirements between the flights ($\zeta'''(r'_{i,j}, S_r) = 1$). Thus the state of a flight-plan segment $r'_{i,j}(t)$, where $j = 1, 2, \ldots, m'_i$; $i, m'_i \in \mathbb{N}$, satisfies AST constraints only when all the above properties take values 1, and thus the function $\zeta(r'_{i,j})$ returns value 'true' when an AST period of a state of the segment $r'_{i,j}$ is feasible.

2.2. Conflicts and resolutions

An AST period of a state of a segment $r'_{i,j}$ has to be re-allocated when the function $\zeta(r'_{i,j})$ (4) returns value 'false'. This might be caused either by a change of meteorological conditions M_t or when a trajectory prediction of flight-plans predicts a conflict at certain times ahead. First, the property $\zeta'(r'_{i,j}, M_t)$, could take value 0 when new meteorological data forbids the AST period of the state of the segment $r'_{i,j}$ which was initially planned using meteorological data M_{t-1} available at the time $t-1$ in the past. This causes the function $\zeta(r'_{i,j})$ to return value 'false'.

Secondly the return of value 'false' by the function $\zeta(r'_{i,j})$ might be caused by either of two types of conflicts that might be predicted at the point of time t. In particular, an AST conflict between the requested flight-plan for clearance r_i and the flight-paths of en-route aircraft $\mathbf{P}$ might occur when either the property $\zeta''(r'_{i,j}, \mathbf{P})$ or the property $\zeta'''(r'_{i,j}, S_r)$ takes value 0 at the point of time t.

When the property $\zeta''(r'_{i,j}, \mathbf{P})$ takes value 0 this means that the AST period of a state of a flight-plan segment ($r'_{i,j}$, where $j = 1, 2, \ldots, m'_i$; $i, m'_i \in \mathbb{N}$) that does not belong to AST occupied or reserved by other flight-plans belonging to $\mathbf{P}$ is not complied with at the point of time t. When the property $\zeta'''(r'_{i,j}, S_r)$ takes value 0 this means that the AST period of a state of a flight-plan segment ($r'_{i,j}$, where $j = 1, 2, \ldots, m'_i$; $i, m'_i \in \mathbb{N}$) which should satisfy the separation requirements S_r between the flights does not do so at the point of time t.

When the property $\eta(r'_{i,j}, A_i)$ (3) takes value 0 then the AST period of the state of the flight-plan segment $r'_{i,j}$ does not satisfy the technical feasibility constraints of the performance characteristics of the aircraft (A_i) allocated to this flight-plan r_i, where $j = 1, 2, \ldots, m'_i$; $i, m'_i \in \mathbb{N}$.

Planning of conflict resolutions is required when an indication occurs either of AST conflict when the property $\zeta(r'_{i,j})$ takes value 0, or of technical conflict when the property $\eta(r'_{i,j}, A_i)$ takes value 0, where $j = 1, 2, \ldots, m'_i$; $i, m'_i \in \mathbb{N}$.

In both kinds of conflicts the automated planning of alterations of the flight-plans has to be undertaken in order to restore the conflict-free status of the set of flight-plans. The IODS systems aim at issuing most efficient clearances within the available resources, monitoring and maintaining their efficiency in the long term. They also aim at ensuring an automated and efficient allocation of air space–time to air traffic and securing conflict-free AST management. It is the claim of the proposed agent-based architecture of a future network of IODS systems that it indicates a new, original and effective way of so doing. It is the claim of the new knowledge management policy that it satisfies the disparate safety and economic concerns of all parties involved in the air traffic industry.

2.3. Knowledge-and-data structures

The aims of the Hierarchies of Objects and Constraints model in Fig. 1 are the design of knowledge of domain-specific objects, of hard and soft constraints, of AST strategies, and of Constraints-satisfaction and Efficiency-optimisation Reasoning (CER) operators associated with various layers of objects with constraints. The HOC knowledge design is hierarchical. It consists of AST knowledge-and-data structures of hierarchical objects, each of which is associated with constraints of a certain kind. It also consists of hierarchies of AST strategies that integrate goal-directed and constraints-propagating principles applicable to hierarchical objects. These hierarchies of CER operators provide the goal-directed decision path generation and constraints ordering principle at various hierarchical levels of acquisition and refinement of knowledge organised in AST knowledge-and-data structures.

This knowledge design aims at facilitating a learning of clearance-categories of flight-plans that satisfy constraints associated with hierarchical objects and that optimise their efficiency. It aims at an integration of knowledge acquisition and reasoning processes that create and refine incrementally hierarchical AST knowledge-and-data structures. Thus it plans and dynamically maintains conflict-free and most efficient flights within the available resources.

The AST knowledge-and-data structures are composed from dynamically created hierarchical objects, air traffic routes, streams of aircrafts, and flight-plans (Fig. 2).

The object of the type *air traffic route* is the securing of a physical two-dimensional route. It comprises a sequence of two-dimensional way points (6). All air traffic routes comprise a set W (5):

$$W = \{W_i \mid W_i = (w_{i,1}, w_{i,2}, \ldots, w_{i,m''_i})\}, \tag{5}$$

$$w_{i,j} = (\text{Longitude}, \text{Latitude}), \tag{6}$$

where $i = 1, 2, \ldots, s$, $j = 1, 2, \ldots, m''_i$, $s, m''_i \in \mathbb{N}$.

If we consider the Organised Track Structure in current use over the North Atlantic it secures the two-dimensional physical routes for air traffic based on weather prognoses nine hours in advance. The tracks remain fixed during the air traffic flow.

The policy's conflict-free planning seeks an advanced, flexible and more efficient AST design and management where the two-dimensional routes W_i (5) where $i = 1, 2, \ldots, s$ are created automatically and updated dynamically in accordance with the overall available AST resources determined by the current meteorological data. These routes are

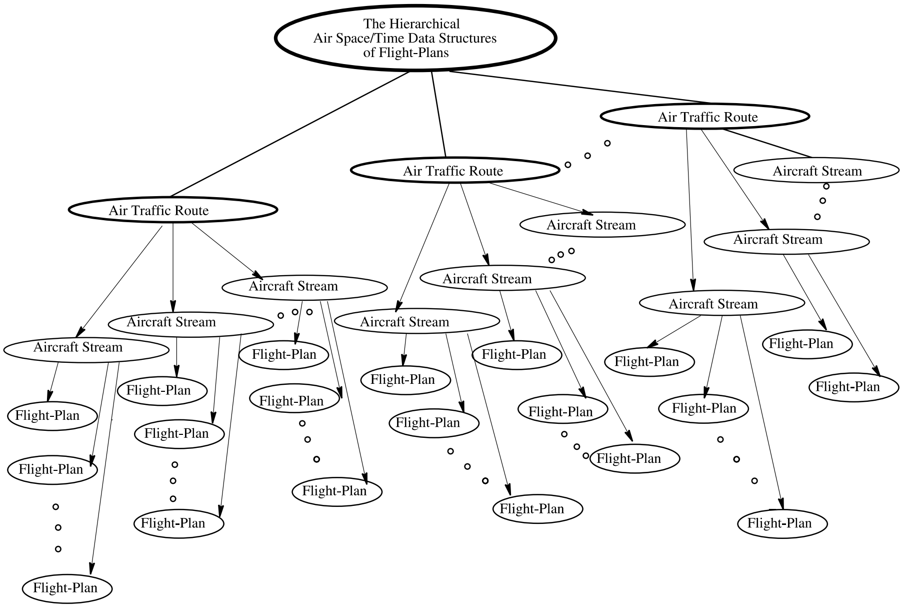

Fig. 2. Hierarchical AST structures.

determined also in accordance with the optimisation of the efficiency of the clearances of the requested flight-plans and the efficiency of the AST use. This is secured by IODS systems, their Agents, and automated knowledge acquisition, CER processes. In response to a queue of flight-plan requests they create and dynamically update a flow of AST knowledge-and-data structures of conflict-free and optimised flights within the available resources. These structures are natural hierarchical structures.

The root of the hierarchy is associated with a set Q of requests of flight-plans and a flow F' (Eq. (17)) of AST knowledge-and-data structures. Each structure contains the conflict-free and optimised flight-plans which are cleared during a certain AST period.

Higher up in the hierarchy is the set W of objects W_i (Eq. (5)) of the type *air traffic route*, where $i \in [1, s]$, $s \in \mathbb{N}$.

In the lower part of the hierarchy there is a set F (7). The set F consists of sets F_i (8) of objects of the type *stream of aircraft* $F_{i,j}$ (9):

$$F = \{F_1, F_2, \ldots, F_s\}, \tag{7}$$

where $s \in \mathbb{N}$.

Below a particular object W_i (Eq. (5)) of the type *air traffic route* there is a particular set F_i (Eq. (8)) of objects of the type *stream of aircraft*. These objects $F_{i,j}$ (Eq. (9)) of the type *stream of aircraft* belonging to the set F_i (Eq. (8)) would inherit the way points of the physical route from the object W_i (Eq. (5)) of the type *air traffic route* higher up in the hierarchy:

$$F_i = \{F_{i,1}, F_{i,2}, \ldots, F_{i,s'_i}\}, \tag{8}$$

where $i \in [1, s]$ and $s, s'_i \in \mathbb{N}$.

The object of the type *stream of aircraft* is the securing of a flow of aircraft following an air traffic route on a particular flight level and separated by the Mach Number (MN) technique.

Each individual object $F_{i,j}$ (Eq. (9)) of the type *stream of aircraft* is described by its set of associated constraints $C_{i,j}$ (Eq. (10)). It is also associated with a set $A_{i,j}$ (Eq. (11)) of individual identification sets of the aircraft that share the *stream of aircraft* $F_{i,j}$ (Eq. (9)):

$$F_{i,j} = \{C_{i,j}, A_{i,j}\}, \tag{9}$$

where $i \in [1, s]$ and $j \in [1, s'_i]$; $s, s'_i \in \mathbb{N}$.

The set of constraints $C_{i,j}$ (Eq. (10)) associated with the object *stream of aircraft* $F_{i,j}$ (Eq. (9)) are:

the entry-time constraint (E_t), the Mach Number constraint (M_n), and the flight level constraint (F_l):

$$C_{i,j} = \{E_{t_{i,j}}, M_{n_{i,j}}, F_{l_{i,j}}\}, \tag{10}$$

where $i \in [1,s]$ and $j \in [1,s'_i]$; $s, s'_i \in \mathbb{N}$.

The set $A_{i,j}$ is consisting of individual identification sets of the aircraft sharing the stream $F_{i,j}$ (9), where $i \in [1,s]$, $j \in [1,s'_i]$ and $s, s'_i \in \mathbb{N}$:

$$A_{i,j} = \{a_{i,j,1}, a_{i,j,2}, \ldots, a_{i,j,s''_{i,j}}\}, \tag{11}$$

where $i \in [1,s]$, $j \in [1,s'_i]$; $s, s'_i, s''_{i,j} \in \mathbb{N}$.

Each individual aircraft identification set $a_{i,j,k}$ (Eq. (12)), where $k \in [1, s''_{i,j}]$ of a particular aircraft contains five identification characteristics which are: the call sign number ($C_{s_{i,j,k}}$), the type of aircraft ($T_{a_{i,j,k}}$), the current speed ($S_{c_{i,j,k}}$) of the aircraft, the current position ($P_{c_{i,j,k}}$) of the aircraft, the current loading ($L_{c_{i,j,k}}$) of the aircraft:

$$a_{i,j,k} = \{C_{s_{i,j,k}}, T_{a_{i,j,k}}, S_{c_{i,j,k}}, P_{c_{i,j,k}}, L_{c_{i,j,k}}\}, \tag{12}$$

where $i \in [1,s]$, $j \in [1,s'_i]$, $k \in [1,s''_{i,j}]$ and $s, s'_i, s''_{i,j} \in \mathbb{N}$.

An object W_i (Eq. (5)) of the type *air traffic route* is associated with a set L_{a_i} (Eq. (13)). The set L_{a_i} contains the range of constraints of the general performance capabilities of various aircraft using the route W_i. The set L_{a_i} consists of sets $L_{a_{i,j}}$ (Eq. (13)) of link indices to various streams of aircraft $F_{i,j}$ (Eq. (9)) in the lower part of the hierarchy, where $i \in [1,s]$, $j \in [1,s'_i]$; $s, s'_i \in \mathbb{N}$:

$$L_{a_i} = \{L_{a_{i,j}} \mid L_{a_{i,j}} = (l_{a_{i,j,1}}, l_{a_{i,j,2}}, \ldots, l_{a_{i,j,s''_{i,j}}})\}, \tag{13}$$

where $i \in [1,s]$, $j \in [1,s'_i]$ and $s, s'_i, s''_{i,j} \in \mathbb{N}$.

The link indices belonging to the set $L_{a_{i,j}}$ (Eq. (13)) comprise the range of constraints values of performance characteristics of the aircraft set $A_{i,j}$ (Eq. (11)) associated with a particular object of the type *stream of aircraft* $F_{i,j}$ (Eq. (9)) in the lower part of the hierarchy, where $i \in [1,s]$, $j \in [1,s'_i]$ and $s, s'_i \in \mathbb{N}$.

The link indices belonging to the set $L_{a_{i,j}}$ (Eq. (13)), where $j \in [1,s'_i]$ are used by the *integrated constraints-satisfaction and efficiency-optimisation goal-directed reasoning*. The AI goal-directed reasoning associates an aircraft request of flight-plan clearance with a particular object of the type *stream of aircraft* in the lower part of the hierarchy. This will be further discussed in the next sections. The objects of the type *AST knowledge-and-data structure of optimised and conflict-free flights* F'_i (Eq. (14)) are as follows:

$$F'_i = \left\{ W'_i, \bigcup_{j \in [1,s'_i]} F'_{i,j} \mid F'_{i,j} = \{C'_{i,j}, A'_{i,j}\} \right\}, \tag{14}$$

where $i \in [1,s]$, $j \in [1,s'_i]$ and $s, s' \in \mathbb{N}$.

On the top of the hierarchy is a *conflict-free and optimised route* W'_i (Eq. (5)) within the available AST resource. This optimised route consists of optimised way-points in respect of the technical capabilities of the aircraft following this route.

In the lower part of the hierarchy there are objects $F'_{i,j}$ (Eq. (14)) of type *stream of aircraft* which are associated with sets of constraints $C'_{i,j}$ (Eq. (10)) and sets $A'_{i,j}$ (Eq. (11)) of aircraft identification sets $a_{i,j,k}$ (Eq. (12)), where $i \in [1,s], j \in [1,s'_i]$; $k \in [1,s''_{i,j}]$ and $s, s'_i, s''_{i,j} \in \mathbb{N}$. An individual object of the type *stream of aircraft* associates flight-plans of aircraft with compatible performance characteristics and efficiency. These flight-plans are also conflict-free and optimised within resources available.

Below particular objects $F'_{i,j}$ of the type *stream of aircraft* (Eq. (14)) there is a set $F_{a_{i,j}}$ (Eq. (15)) of *conflict-free and optimised flight-plans* of the aircraft sharing the stream. Each of these individual flight-plans $F_{a_{i,j,k}}$ (Eq. (16)) relates to a particular aircraft identification set $a_{i,j,k}$ (Eq. (12)) of aircraft originating the clearance request, where $i \in [1,s]$, $j \in [1,s'_i]$; $k \in [1,s''_{i,j}]$ and $s, s'_i, s''_{i,j} \in \mathbb{N}$.

Thus the set of *conflict-free and optimised flight-plans* $F_{a_{i,j}}$ (Eq. (15)) associated with the *object stream of aircraft* $F'_{i,j}$ is as follows:

$$F_{a_{i,j}} = \{F_{a_{i,j,1}}, F_{a_{i,j,2}}, \ldots, F_{a_{i,j,s''_{i,j}}}\}, \tag{15}$$

where $i \in [1,s]$, $j \in [1,s'_i]$ and $s, s'_i, s''_{i,j} \in \mathbb{N}$.

An individual flight-plan $F_{a_{i,j,k}}$, (Eq. (16)) where $i \in [1,s]$, $j \in [1,s'_i]$, $k \in [1,s''_{i,j}]$ and $s, s'_i, s''_{i,j} \in \mathbb{N}$, comprises a sequence of four-dimensional segments. The number of the segments and the length of the AST period of the segments is not fixed. It could vary. A learning process could split or merge segments of a fight-plan during CER:

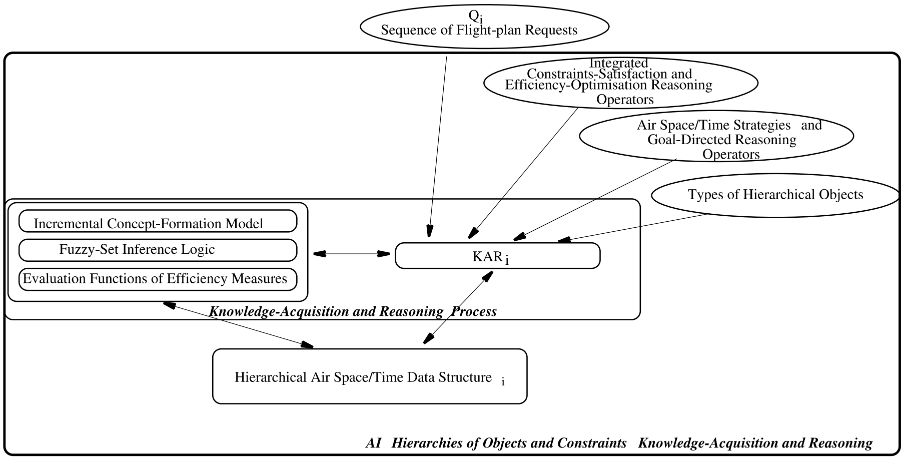

Fig. 3. Hierarchies of objects and constraints.

$$F_{a_{i,j,k}} = \{S_{a_{i,j,k,1}}, S_{a_{i,j,k,2}}, \ldots, S_{a_{i,j,k,s'''_{i,j,k}}}\}, \quad (16)$$

where $i \in [1, s]$, $j \in [1, s'_i]$, $k \in [1, s''_{i,j}]$ and $s, s'_i, s''_{i,j}, s'''_{i,j,k} \in \mathbb{N}$.

The conflict-free planning seeks a flow F' (Eq. (17)) of *AST knowledge-and-data structures of conflict-free and optimised flights* F'_i (Eq. (14)), where $i \in [1, s]$, $s \in \mathbb{N}$. It is created from a queue of flight-plan clearance requests Q (Eq. (2)). The queue of the flight-plan requests Q and the resulting flow F' (Eq. (17)) of AST data structures of conflict-free and optimised flights F'_i (Eq. (14)) are associated with the root of the hierarchy:

$$F' = \{F'_1, F'_2, \ldots, F'_s\}. \quad (17)$$

The Conflict-Free Planning associates a flight-plan clearance with a certain *conflict-free and optimised route* (W'_i) and a *stream of aircraft* ($F'_{i,j}$), if and only if it is the most efficient clearance given the available resources.

2.4. Knowledge generation

The sequence of new flight-plan clearance requests is a set of non-accounted events. It is associated with the root of the hierarchical AST structures. The IODS systems allocate AST resources to requested flights by automated knowledge-acquisition and reasoning processes of Hierarchies of Objects and Constraints components (see Fig. 3). Their design forms an application of concept-learning [7] of knowledge-and-data structures, and incremental concept-formation [9], fuzzy logic and probabilistic reasoning [8] in forming concepts of *clearance categories* of flight-plans. It applies also efficiency measures and evaluation functions in optimising the efficiency of these categories and in maintaining the long term efficiency of flights and air space–time use. It organises these categories in hierarchical objects of AST knowledge-and-data structures.

The concept-learning [7] aims at generating decision support knowledge. Applied to a sequence of flight-plan clearance requests it learns alternative concepts of *clearance categories* and organise these concepts in hierarchical structures. It creates the hierarchical objects of *clearance categories* incrementally and dynamically updates the existing ones in response to new flight-plan requests. It creates different clearance categories in parallel. Thus it examines the efficiency which various clearance categories provide for the sequence of flight-plans requested for clearance. It arranges the clearance requests in priority and accords with their efficiency requirements and the efficiency of the AST reservation by the use of the domain-specific CER operators.

The logic of making inference of clearance categories of flight-plans creates fuzzy sets of the characteristic values of instances of flight-plan clearance-requests and associates these with the degree of their affiliation to the individual conceptual clearance categories. The domain-specific functions in the air traffic domain would calculate the degree of affiliation and the degree of non-affiliation, for example, of requested optimal values of flight-levels of flight-plans to various overlapping clearance categories. The created fuzzy sets help the estimation of the efficiency that these individual overlapping clearance categories would provide for the individual flight-plans. The degree of affiliation helps in finding the most efficient clearance category for the flight-plans. The final hierarchical objects of the most efficient clearance categories and their mean values (for example of the flight-level or way points of route), are those that would accommodate the greatest number of conflict-free and optimised flight-plans given the available resources.

The parallel concept-formation processes incrementally create, update and operate the acquired knowledge of a hierarchy of AST structures in response to new flight-plan clearance requests. They also arrange in priority the clearance of the sequence of flight-plans, and acquire their most efficient clearance categories. They organise the acquired knowledge of the clearance categories of sets of flight-plans in a flow of AST knowledge-and-data structures of conflict-free and optimised flights.

3. The agent-based architecture

The conflict-free planning of air traffic can be accomplished. An agent-based architecture of a future global network of Integrated Operational Decision Support Systems for airlines and airports, and air traffic control and management will do this.

The IODS systems manage the AST resources and technical capabilities of aircraft under current loading. They generate decision support knowledge about maintaining the efficiency of flight-plans and their AST use by collaboration between dynamically created groups of agents within the agent-based architecture of the network of the integrated systems. They manage the sequence of flight-plan requests by issuing their most efficient clearances within the available resources. They monitor and maintain their efficiency in the long term.

The agent-based architecture of the future network of IODS systems for airlines and air traffic controllers is an open architecture and software agents are used for constructing it. The agents encapsulate data and knowledge, efficiency measures and evaluation functions, tasks and objectives, and reasoning capabilities to achieve them. The agents exist and operate within an environment which is a certain hierarchical layer of the architecture (see Fig. 4).

3.1. Hierarchical layers

The five general hierarchical layers of components of the agent-based architecture are given in Fig. 4. These layers represent Agents managing the five main components of the architecture. Each of them communicate with the Agents managing

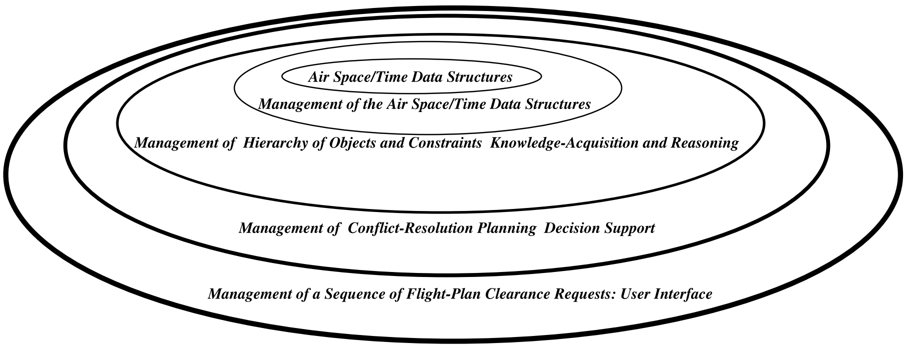

Fig. 4. Hierarchical layers.

components in the adjacent hierarchical management layers.

The most external management layer represents the user-interface component managed by an Agent-manager of the sequence of flight-plan requests. This Agent communicates with the Agent-manager of the Planning of Conflict-Resolution (PCR) decision support component. The Agent-manager of the PCR decision support communicates with the Agent managing the hierarchies of objects and constraints Knowledge-Acquisition and Reasoning (KAR). The Agents managing parallel KAR processes are associated with the lower part of the internal hierarchy of the main management layer of the hierarchy of objects and constraints. These Agents communicate with the Agent managing the AST. The latter Agent manages the AST knowledge-and-data structures of conflict-free and optimized flights in the innermost hierarchical management layer. These AST structures are monitored by Agents managing parallel monitoring processes. The latter agents are associated with the internal hierarchy of the AST layer.

The Agent-managers of the main components have their own sub-hierarchy of Agents. The latter agents communicate with each other within the layer of their components or with agents in the internal hierarchy of adjacent layers of components. They have their knowledge, tasks, objectives, relevant reasoning capabilities and own hierarchical level of influence within the management layers of the agent-based architecture.

3.2. Agents and cooperation

There are the following general types of agents: aircraft agents and interface agents, decision support agents, AST allocating and monitoring agents and Knowledge-Acquisition and Reasoning agents. These agents have a certain hierarchical role and influence in the process of generation of decision support knowledge. The agents managing the KAR processes have the top responsibilities. They interact with each other within dynamically created groups of agents. These groups are created on demand and comprise the most suitable and available agents for a certain task. Interactive groups of agents operate either within one hierarchical layer or within adjacent hierarchical layers of the system.

Fig. 5 shows the cooperation between agents managing AST allocation and monitoring, and agents planning clearances and alterations of flight-plans, and generating decision support knowledge. These involve the cooperation between aircraft agents, user-interface agents, AST managing agents and agent managing Hierarchies of Objects and Constraints component.

The AST managing agents monitor the flow of AST knowledge-and-data structures of conflict-free and optimised flights and cooperate with the agents managing the parallel KAR processes of the AI Hierarchies of Objects and Constraints component. The latter agents maintain the flight plans within the available resources.

The agent managing the Hierarchies of Objects and Constraints KAR component is also an agent-manager of all parallel KAR processes. Each of these parallel KAR processes is managed by an agent in the internal hierarchy of the management of the AI Hierarchies of Objects and Constraints component. The agent managing an individual KAR process creates an AST knowledge-and-data structure of conflict-free and optimised flights requested for clearance during a certain AST period.

The flow of AST knowledge-and-data structures of conflict-free and optimised flights within the available resources is generated and also maintained by parallel KAR processes. Each of these KAR processes maintains an individual AST knowledge-and-data structure of flights of en-route aircraft. This is managed by an agent-manager of the individual KAR process in co-operation with the AST agent monitoring the structure. An individual KAR agent establishes a cooperative relation with other KAR agents via the Agent managing the Hierarchies of Objects and Constraints component higher up in the hierarchy of management layers. An individual KAR agent establishes a cooperative relation with an Agent monitoring the AST knowledge-and-data structure in the AST layer via the Agent-manager of the AST component.

This Decision Support Component is based on the Hierarchies of Objects and Constraints component and its parallel KAR processes. The KAR

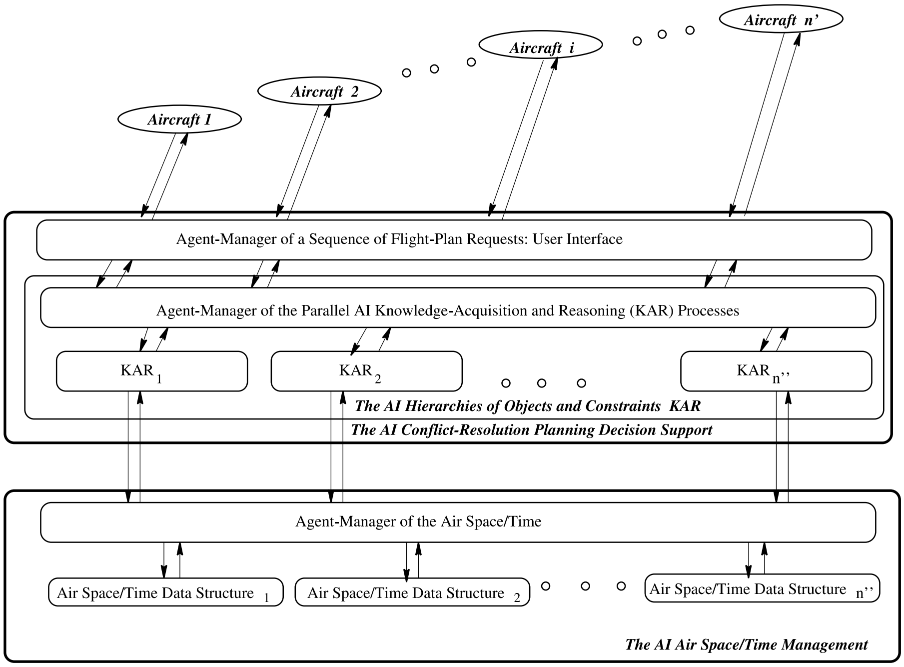

Fig. 5. Decision support.

agents also cooperate with the aircraft agents via the interface agents of the user interface component managing the sequence of requests. Thus they accord with the efficiency of flight-plans requested for clearance. They accord also with the efficiency of AST use. The most effective solutions of the flight-plan clearances during a certain AST period are those that optimise the efficiency of the individual flight-plans and the general efficiency of AST reservation. The agent managing the Hierarchies of Objects and Constraints component organises these most effective solutions of the flight-plan clearances in hierarchical AST knowledge-and-data structures.

The agents managing the monitoring processes of the AST layer cooperate with the KAR agents of the Hierarchies of Objects and Constraints layer. Thus the agent-based architecture integrates two main components that of managing AST and predicting possible conflicts and that of planning of their resolutions off-line and generating decision support knowledge for keeping the flights conflict-free. The automated integration of these components (Fig. 5) and the cooperation between their intelligent agents secures together the conflict-free planning for air traffic management.

The IODS systems manage the use of AST in a flow of AST data structures of conflict-free and optimised flights given the available resources. The flow of the AST knowledge-and-data structures is a dynamically changeable hierarchical structure of flight-plans (Fig. 2) optimised within the available resources.

The Agent-manager of the AST component (Fig. 6) manages the use of the AST resources by Agents managing the monitoring of the AST knowledge-and-data structures. An individual agent monitors a structure by trajectory prediction of the states of the flight-plans associated with it during a certain AST period ahead.

When an indication of a prediction of an AST conflict occurs then the Agent requests a maintenance service concerning the conflict-free and efficient use of the AST. The service is provided by the Agent managing the decision support component higher up in the hierarchy and its Agents

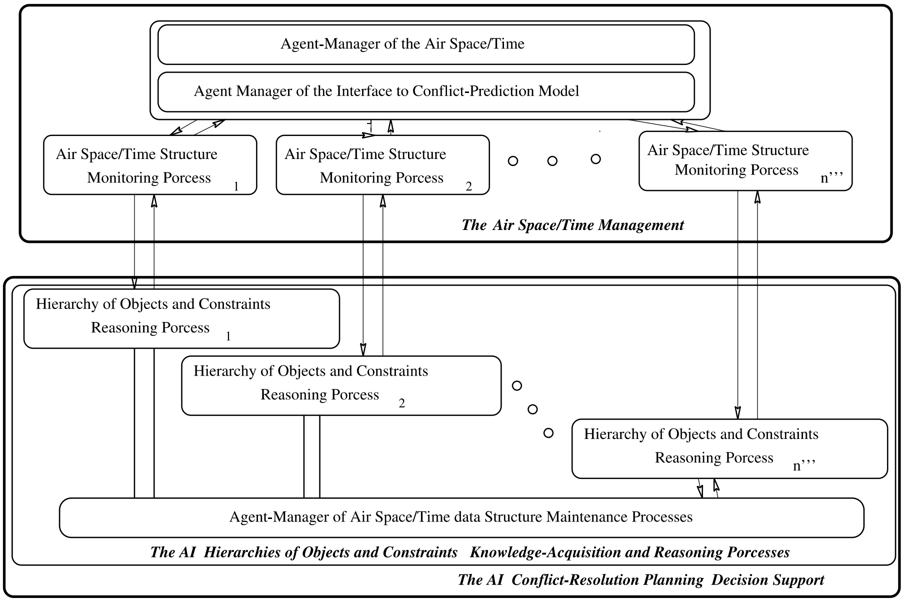

Fig. 6. Air space–time management.

managing the parallel KAR processes of the Hierarchies of Objects and Constraints layer. The Agent managing a particular KAR process generates knowledge about most efficient alterations of the flight-plans well in advance before the AST can develop in real-time. Thus the service keeps the AST knowledge-and-data structure of flight-plans conflict-free and the AST most efficiently used. This service is provided by the Hierarchies of Objects and Constraints component (Fig. 3) and by its domain-specific hierarchies of AST strategies and of integrated constraints-satisfaction and efficiency-optimisation goal-directed reasoning.

3.3. Tasks and interactions

The following general tasks involves interactions between dynamically created groups of agents:

- managing a sequence of flight-plan requests,
- generating and dynamically updating hierarchical AST knowledge-and-data structures of conflict-free and optimised flights,
- clearing efficient flight-plans within the resources available,
- planning of conflict-resolution alterations of flight-plans off-line during a certain AST period in advance, and
- managing the communications between the IODS systems and the users.

The management of the flight-plan request queue involves collaboration and interactions between the interface agents of the clearance requests queue component and the KAR agents of the Hierarchies of Objects and Constraints component. The agents monitoring the AST structures collaborate with the Agents managing the KAR processes. Their joint work secures an automated generation of a flow of hierarchical AST knowledge-and-data structures of conflict-free and optimised flights from flight-plans which have been received, and arranges whatever alterations in them are necessary for ensuring their most efficient clearances.

When an AST monitoring agent predicts an AST conflict during a certain AST period ahead, it requests planning of conflict-resolution alterations of flight-plans from an agent managing a relevant KAR process. The AST agent collaborate with the KAR agent in allocating conflict-free AST resources for alterations of flight-plans.

Both interface agents and the AST management agents interact and collaborate with the agents managing the relevant KAR process. These parallel groups of collaborative agents are created dynamically in response to flight-plan requests.

The clearance request queue agents and the aircraft agents are in communication with each other constantly. They collaborate and operate in the network of IODS systems on behalf of the user, pilots and controllers. The aircraft agents aim at the optimisation of the efficiency of the flights. The KAR agents aim to maximise the efficiency of AST use on behalf of the global system.

The decision support agents acquire knowledge through the Hierarchies of Objects and Constraints component. This component enables them to learn about the most efficient clearances of a sequence of flight-plans. Through this component they also learn how to maintain the flight-plans conflict-free and optimised within the available resources.

The agents managing parallel KAR processes acquire and incrementally update a flow of AST data structures of conflict-free and optimised flight-plans in response to a sequence of flight-plan clearance requests. If required they plan alterations of sets of flight-plans well in advance to keep the AST conflict-free and most efficiently used. Agents managing the parallel processes (Fig. 6) monitor AST knowledge-and-data structures. When a conflict indication occurs the Agents pick up the objects from the structures and communicate with the agents managing KAR processes to restore the efficient state of these structures by altering their flight-plans well in advance before any conflict develops. These Agents establish the new most efficient state of the flight-plans given the available resources.

The alterations of the particular flight-plans are communicated to the air traffic controllers and the airlines and their pilots by the decision support agents via the user interface of the integrated systems. The communications between the IODS systems are the tasks of the agents of the user interface components of these systems. The objectives are fast and secure communication of the flight-plan alterations and clearances in response to requests.

The interface agents observe the sequence of flight-plan clearance requests (Fig. 5) and organise it in a queue of requests in time priority order. They inform the Agents managing the Hierarchy of Objects and Constraints components of this.

The Agent managing the Hierarchies of Objects and Constraints component (Fig. 5) deals with the queue of flight-plan requests, establishes their priority, allocates their conflict-free air space–time and optimises their efficiency according to the available resources. The Agent accomplishes this by starting parallel KAR processes with sub-sequences of flight-plans requested during a certain AST period.

In dealing with new clearance requests the Agent-manager of the Hierarchies of Objects and Constraints layer distributes these to the Agents running the relevant KAR processes. An individual KAR Agent (Fig. 3) manages its internal parallel concept-formation processes. These processes learn the concepts of categories of clearances of flight-plans. The aims of these processes are to find the most efficient clearance of a flight-plan within available resources during a certain AST period. The Agents running parallel KAR processes explore all available AST resources for all possible clearance-categories of flight-plans, and thus they learn how best to clear them and reserve AST for them.

In order to deliver this the Agents managing individual KAR processes (Fig. 3) are in touch with the Agent managing the Hierarchies of Objects and Constraints component (Fig. 5). They seek to ensure the most efficient clearances and they may exclude a particular clearance request from the sub-set of clearance requests dealt by the KAR process. The request will be included in subset of requests dealt with in a selected KAR process having relevant AST resources to ensure the most efficient clearances of the requests.

As a result the Agents managing parallel KAR processes generate and maintain a flow of AST structures of optimised and conflict-free flights. Each of these structures is a product of a KAR process, resolving a certain subsequence of flight-plan clearance requests during a certain AST period.

The Agents of individual KAR processes and the Agents managing the AST (Fig. 5) cooperate concerning functions such as the available ASTresources and the updating operations on hierarchical objects of AST data structures. These operations aim at efficient allocation of the AST resources for certain requests of flight-plans. The Agent-managers of parallel KAR processes deal with the requests and communicate in return the alterations and clearances of the flight-plans to the Agents managing the decision support and the user interface of the IODS systems.

3.4. Objectives

The objectives are the provision of decision support knowledge for pilots and controllers concerned with the efficient allocation of AST resources and maintenance of a flow of AST knowledge-and-data structures of conflict-free and optimised flights given the real-time available resources and flight-plan requests.

The KAR agents aim at an incremental acquisition and refinement of a knowledge of most efficient clearance-categories of flight-plans organized in hierarchical AST knowledge and data structures of flight-plans from a set or sequence of flight-plan requests. Creating a new clearance-categories or refining already existing ones organised in hierarchical objects of AST knowledge and data structures is in response to requests and reasoning about their most efficient resolutions.

An Agent managing a particular parallel KAR process starts with an input structure of the type of the hierarchical knowledge-and-data structure. This input structure contains the hierarchical objects of flight-plans during a certain AST period. It can be either the Organised Track Structure created nine hours before the air traffic flow starts, or be created incrementally by the KAR processes when flight-plan clearances are requested.

The KAR process (Fig. 3) brings about dynamically changes in the hierarchical objects during parallel concept-formation processes about the satisfaction of hard resource constraints and the optimisation of efficiency objectives within a certain AST period. The process may, for example, change the flight level of an aircraft; thus, it changes the stream of the aircraft to a new one or originates a new object of the type stream of aircraft. It may change the original way-points of the flight-plan of aircraft to new optimised way-points; thus the reasoning process changes the air traffic route of the flight-plan. The result of an individual KAR process is an AST data structure of conflict-free and optimised flights. The parallel KAR processes (Fig. 5) deal with the sequence of flight-plan requests and the result is a flow of AST knowledge-and-data structures.

When the flight-plan clearances are requested the IODS systems can transform, for example, the original OTS over the North Atlantic created nine hours before the air traffic flow starts, into a flow of AST data structures of conflict-free and optimised flights given the resources available. The IODS systems also can create incrementally a flow of AST data structures of conflict-free and optimised flights when the flight-plans are requested. Thus there would be no use of OTS created nine hours in advance.

The KAR processes (Fig. 3) take into account the recent weather forecast as a part of the AST constraints, and the current loading of various aircraft in addition to a knowledge of the technical feasibility constraints, and the efficiency cost functions of flight-plans deduced from the technical characteristics of aircraft. The IODS keeps the flights conflict-free and optimised given the real-time resources available during the flow of the air traffic.

The proposed policy and its IODS systems for an automated airspace design and conflict-free planning for air traffic is relevant to both, Oceanic airspace and domestic airspace.

4. Conclusions

This policy seeks to ensure more efficient future air traffic control and management by providing an automated global planning of air space–time use as a response to an ever growing and urgent need. Air traffic is increasing and pressure on all airports growing. The air traffic industry is looking for new strategies which will safely add to airspace capacity and make the best use of available resources. It is the claim of this paper that the policy here proposed will enable this to be done.

The policy brings conflict-free planning for air traffic supported by a global network of integrated operational decision support systems for airports, airlines and air traffic control. These systems ensure planning of conflict-free AST use off-line before an aircraft can be safely airborne, monitoring the flights and keeping them conflict-free and the air space–time efficiently used in the long term. This means fewer cancelled and delayed flights. It also means easing the workload of the air traffic controllers and securing the efficiency of air traffic management with the fewest interventions in real-time.

The policy provides the integrated operational decision support for pilots and controllers. This means better management of knowledge and air traffic. It also saves the airlines a great deal of money, and the passengers a great deal of time.

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References

[1] P. Gibbs, HIPS Phare Highly Integrated Problem Solver Version 4 API definitions European Organisation for the Safety of Air Navigation EUROCONTROL, Eurocontrol Experimental Centre, Task R04, EEC Note 12/97, Version 1.2: November 1996.
[2] HIPS, Application of HIPS to Oceanic Control, UK National Air Traffic Services, NATS R&D Report 9710, Hurn, UK, 1997.
[3] B. Iordanova, An agent-based architecture of future integrated operational decision support systems for conflict-free planning for air traffic management, in: Proceedings of the Third International Conference on Enterprise Information Systems ICEIS-2001, vol. 1, July 7–10, 2001, pp. 509-513. Available from http://www.Icies.org, ISBN: 972-98050-2-4.
[4] B. Iordanova, Conflict-resolution planning relevant to decision support systems for future air traffic management, Doctoral Dissertation, University of Huddersfield, UK, British Library, March 2000.
[5] B.N. Iordanova, Towards conflict resolution planning: a set-theoretic model, in: Workshop on Planning as Combinatorial Search, held on in conjunction with the International Conference Artificial Intelligence Planning Systems 98, Carnegie Mellon University, Pittsburgh, June 1998.
[6] B. Iordanova, Resolving conflicts between flight-plans: planning aspects of the problem, in: 16th UK Planning and Scheduling SIG, December 1997, pp. 105–118.
[7] B. Iordanova, Decision support system BIOR, in: Proceedings of the First ECPD International Conference on Advanced Robotics and Intelligent Automation, Athens, Greece, September 1995.
[8] B. Iordanova, Intuitinistic fuzzy sets and incremental concept formation in artificial intelligence, in: Periodical BUSEFAL, Institute de Recherche en Informatique de Toulouse (URA-CNRS 1399), Université Paul Sabatie, France, vol. 62, Spring 1995, pp. 8–16, ISSN 0296-3698.
[9] B. Iordanova, Incremental concept formation model, in: Proceedings of the Conference of the ACMBUL, Varna, September 1993.
[10] G. Maignan, What is PHARE? Air Traffic Control Quarterly 2 (2) (1994).
[11] C. Meckiff, P. Gibbs, The PHARE Highly Integrated Problem Solver, European Organisation for the Safety of Air Navigation EUROCONTROL, Eurocontrol Experimental Centre, Task AT59, EEC Report 273,1994.
[12] C. Meckiff, Conflict-resolution support for random routing, Air Traffic Control Quarterly 6 (2) (1998).
[13] NATSIM, Functional design specification for NATSIM V1.200, Smith document DA214D001-1.2, Smith System Engineering Ltd., Guildford, UK, 1997.
[14] NATSIM Software design specification for NATSIM V1.200, Smith document DA214D002-1.2, Smith System Engineering Ltd., Guildford, UK, 1997.
[15] NOAA, New Optimisation Approaches to Air Traffic Flow Management, FINAL REPORT Sequencing, speed control, multi-sector planning and their inferences, NOAA/WP3/V0.1, WORK STREAM WP3.3a Cost function in ATFM optimisation problems, SOFREAVIA/INRETS, 1 October 1996.
[16] PHARE, Experimental Problem Solver, Implementation 1, European Organisation for the Safety of Air Navigation EUROCONTROL, Eurocontrol Experimental Centre, Task AT59, EEC Note 20/94, 1994.

[17] T.S. Perry, The truth about the air traffic control, IEE SPECTRUM (August) (1997).
[18] A. Price, C. Meckiff, HIPS and its Application to Oceanic Control, FAA/Eurocontrol R&D Symposium, Paris, 17–20 June 1997.
[19] J.P. Prince, An Overview of NATSIM: The North Atlantic Simulation Model, Strategy and Development Directorate, National Air Traffic Services Limited, R&D Report S&DD File Reference 8RD/14/024/01, September 1997.
[20] P.G. Whicher, ATM Conceptual Evolution – Tubes of Flight? in: Proceedings of the European Air Traffic Management – Will It Meet the Demand? November 24, 1993. Published by the Royal Aeronautical Society, ISBN 1-85768-1606, 1993.