A COMPLEX SYSTEM APPROACH IN MODELING AIRSPACE CONGESTION DYNAMICS

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ABSTRACT
The dynamical behaviour of groups of airspace sectors, *e.g.* Functional Airspace Blocks, is not trivial to be analysed without appropriate theoretical tools. In this paper, we suggest a discrete model based on cellular automata and multi agent systems to express the congestion dynamics and complexity in the controlled airspace. Discrete time simulations have been performed with random selected scenarios of traffic and with independent sector parameters to investigate the impact of availability of local sectors on the whole state of the airspace. Obtained results show the existence of a traffic threshold that leads to a theoretical saturation of airspace. The test scenario showed a phase transition phenomenon towards the congestion of the European airspace at the resulting traffic threshold *circa* 50 000 flights. Validation using real data shows the predictive abilities of the model.

Keywords: Air Traffic Management, Air Traffic Control, Complex Systems, Airspace availability, complex networks, Multi Agent Systems, cellular automata.

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1. INTRODUCTION

Most of new policies trying to improve the Air Traffic Management (ATM) system tend to maintain its classical structure. Innovation in this field is basically focused on equipment, information and communication technologies, task automatization and improvement of Human-machine interfaces [Watkins et al., 2002]. Nevertheless, different actors of airspace traffic consider that the current system has attained its limits and congestion is more and more difficult to resorb. Empirical studies show that more and more network-effects are observed in the operational context demonstrating the qualitative changes in the airspace availability ([Mayer et al., 2003], [Daniel, 1995], [Brueckner et al., 1992]).

Delay cost is evaluated to be between 7 and 11 billion euros per year and according to the Institute of Air Transportation (IAT) 60% is due to ATC (Air Traffic Control) [ITA, 2000]. The ATM system is composed of numerous processes and various actors having different and divergent objectives: pilots try to be on time, companies focus on economic aspects (reducing costs and maximizing benefits) and controllers must guarantee the security of the traffic. In our approach, even if we tried to include indirectly some ATM aspects, we are basically concerned with the ATC subsystem, in particular the *en route* control. In fact, en route control in Europe is the main responsible of traffic delays leading to costs of several billion euros per year [Golaszewsk, 2002]. This is not the case in the USA where delays are caused by the airport saturation.

Air Traffic Management (ATM) can be modelled as a set of components of different subsystems in mutual interactions in order to accomplish the mission of simultaneously maintaining safety and sustaining growth. The ATM system is considered as a complex system because its behaviour depends on a complex combination of various sub-systems performing complicated functions. The evaluation of the impact of each function on the overall ATM system cannot be performed unless a specific approach is used. Understanding the mechanisms by which complexity may be reduced in the particular domain of ATM may provide important solutions to optimize the dynamics of the system and its structure.

2. OVERVIEW OF THE ATM SYSTEM

The Air Traffic Management system is a complex network composed of several heterogeneous and mutually interacting subsystems. The complexity of the ATM can be related to the following factors: system size, diversity of users, safety constraints and uncertainty (weather, human factor, technical factor...). This complexity can be also related to the Air Traffic Control (ATC) subsystem representing the rigidly structured air space and the largely centralised, human operated control hierarchy ([Delahaye et al., 2005], [Histon et al., 2002]). ATC, in which we observe complex phenomena, is composed of services provided by the controllers on the ground to ensure the safety and the efficiency of aircraft's motion, and are provided throughout the controlled sectors. In fact, aircraft tend to fly along fixed corridors and at specific altitudes, depending on their route. The entire path of the aircraft is pre-planned (flight plan) and only minor changes are permitted online. The ATC is in complete command of the air traffic and ultimately responsible for safety. All requests by the aircraft have to be cleared by the ATC.

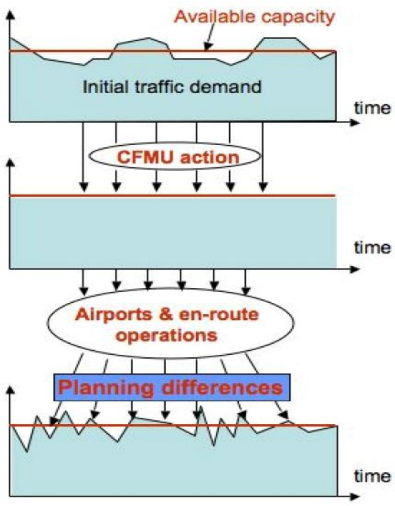
Airspace is composed of controlled airspace and uncontrolled airspace. A controlled airspace is a set of controlled sectors, each of which being associated to a team of air traffic controllers. These air traffic controllers are persons who operate the air traffic control system to expedite and maintain a safe and orderly flow of air traffic, and help prevent mid-air collisions. They apply separation rules to keep each aircraft apart from others in their area of responsibility and move all aircraft efficiently through "their" airspace and on to the next. [Tran Dac, 2004]

Aircraft follow a planned trajectory to join two airports. They are monitored and guided throughout the whole flight time by air traffic controllers. Computers, communication links and radar screens all provide up-to-date information. Technology quite often has not one but two back-up systems to cover any possible breakdowns. The whole organisation is based upon international regulations and determined routines. During the flight different services are furnished by three kinds of control activities: Tower Control where controllers direct aircraft that are taking off or landing at airports, Approach Control where controllers handle aircraft that are transitioning from the en-route portion of flight into the airspace around or near an airport and En-route Control where controllers handle aircraft that are operating on the main travel portion of their flights, typically at a high altitude.

As specified in the introduction, in this work, we are especially interested in the study of the behaviour of the en route sectors because, in Europe, en route control is the main responsible for the airline delays and traffic congestion. We include the effects of approach and tower control sectors using a non-local interaction rules. As we can see in Figure 1, the initial traffic demand exceeds the declared capacity of a sector at a specific moment. The Central Flow Management Unit (CFMU), an operational unit of EUROCONTROL[3], manages air traffic demand in order to avoid airspace congestion due to this difference and to optimize the utilization of resources. Despite the regulation and the planning made by the CFMU there are always differences between planned and real traffic. These differences are specific to each sector and the resulting effect of these local states and their interactions between them on the whole availability of airspace are difficult to determine.

By considering the densely interconnected system of ATM as a network where components properties are heterogeneous and individual and by applying appropriate theories we are able to model the emergence of global properties in the system from the local behaviour of its component (typically the availability and congestion of the airspace). By this way we can take into account the coordination requirements representing the interactions between controllers in adjacent sectors, which is an important factor in ATC complexity [Histon et al., 2002]. It is also important to note that these interactions are closely dependent of the airspace design. In fact the topological structure of airspace defines the structure of the sectors coordination network. The space-time analysis that we propose in this paper is a general approach focusing on the intricate relation between these two fundamental aspects.

Figure 1 Real versus planned traffic in a congested sector



[3] EUROCONTROL is the European Organization for the Safety of Air Navigation

3. BOTTOM-UP MODELING OF THE ATM SYSTEM

ATM simulation requires a modelling approach and simulation framework taking into account particularities and properties of this system. ATM being a complex system where the objective is to guarantee the security and fluidity of the traffic by optimizing the use of the shared resources between different actors having divergent constraints (companies, air traffic controllers, pilots, passengers...) needs to be studied using appropriate Tools [Boccara, 2004].

In various natural and artificial contexts, we observe phenomena of high complexity. However, research in physics, biology and in other scientific fields showed that the elementary components of complex systems are quite simple. It became crucial for scientific research dealing with complex systems to determine the mathematical mechanisms to understand how a certain number of such elementary components, acting together, can produce the complex behaviours observed in these systems.

Cellular automata studied by Stephen Wolfram [Wolfram, 1984] represent an attempt to design the simplest mathematical model able to generate a high complexity. One of the most important current problems consists in finding general laws being able to be applied to study the majority of complex systems. A cellular automaton is, in the simplest case, one line made up of empty boxes. Each box carries one value 0 or 1. Thus, the system configurations are an ordered sequence of 0 and 1 evolving over time. At each time step, the value of each site is updated according to a specific rule. The rule depends on the value of a cell, and of its two closest neighbours.

According to Wolfram [Wolfram, 1986], [Wolfram, 1994] Cellular Automata (CA) are microscopic models for complex natural systems containing large numbers of simple identical components with local interactions. Even if the construction of the cellular automata is very simple, their behaviour can be very complex [Wolfram, 1994], [Wolfram, 2002]. There are fundamental reasons showing that there is no general method which can universally be applied to predict the behaviour of these systems. Compared with reality the cellular automata appear simplistic. However, they are currently considered as a fundamental tool in modelling and simulating complex phenomena, in particular concerning the auto-organized systems. The use of the cellular automaton makes it possible to reduce the complexity of modelling to what is necessary to generate the phenomenon. It is a paradox of complex systems: the behaviour of the system is unpredictable and complex (at a long term level) whereas the laws (or rules) which controlling it are simple and deterministic. Moreover, cellular automata represent a powerful simulation tool. In fact a convincing simulation of large dataset requires computing power of parallel computers. However, the local nature of interactions between cells makes the programming of cellular automata easy "to be parallelized". The dynamic theory of systems was developed to describe the global properties of the solutions of equations.

A combination of Cellular Automata (CA) formalism and Multi Agent Systems (MAS) allows a coherent mathematical and computational representation of the physical model. In fact, CA permit the representation of the entities composing the system and the evolution of their state over time whereas MAS are well adapted to express the interactions between the entities and their behaviour [Weiss, 1999], [Fikes, 1982]. We will use in our model this combination to rebuild the real system from the basic components.

a. WHY CA AND MAS IN ATM MODELING?

The interest in combining MAS and CA is to introduce the mobility of the components representing the cells of CA. These components are called *agents* in MAS and they are able to move, communicate, transmit information, take decisions and influence their environment. Generally, agents are used in social sciences to represent individual or collective decisions in a population and more generally they have socio-economical attributes. But multi agent simulations in social sciences are often non-spatial which is not the case in ATM. In fact, in ATM modelling we need to represent:

The physical and geographical system (airspace) and its properties:

- structure dynamics : evolution of the merging and splitting schemes of the sectors.
- routes and sectors topology (shape of the sectors, average number of neighbours, routes configuration,...).
- the technical system : aircrafts, communication systems...
- human system : controllers, pilots, ...

In order to provide an efficient and realistic simulation of the ATM behaviour it is important to include the relations between its three basic subsystems. In fact, the components of technical subsystem (aircrafts) interact with the physical subsystem (sectors) and the human subsystem (controllers, pilots). The human subsystem is particularly important because it supervises the two other subsystems in order to accomplish the global mission of the ATM system: manage the continuous increase of the traffic volume while guaranteeing the security and the fluidity of the traffic. These aspects can be easily integrated by combining CA and the multi agent paradigm.

Actually, complexity of ATM (combination of a natural and an artificial complex system) is such that even a MAS/CA simulation is insufficient to capture all the aspects and specificities of the system. A realistic representation of ATM needs the representation of hierarchy and heterogeneity of the different subsystems. Nevertheless, in our work we are especially interested in observing qualitatively the behaviour of the system while reproducing in a simplified way its basic mechanisms.

Here is the list of the important aspect which must be considered in the modelling of the ATM system:

- the different kind of entities in the system;
- the different hierarchical levels in the system;
- the topology of the entities;
- the different kind of relations between the entities;
- the process determining the state of the entities;
- the process determining the changes in their spatial location.

The simulation of the behaviour of such a system needs a rigorous formulation of these aspects. The simulation of the management of shared resources requires also the integration of the interaction between the agents and the dynamical resources. A first method that could be used to represent these interactions emphasize on processes determining interactions between agents and resources. These agents are cognitive agents having a representation of the resource and possess their own rules to reach their objectives. Each agent acts on the resource according to his rules and modify the resource for other agents. In our context we are facing the problem of the management of renewable common resources (airspace) in confrontation with different actions and situations which may lead to a satisfactory use (or not) of the resource for the different agents (pilots, controllers, companies,...).

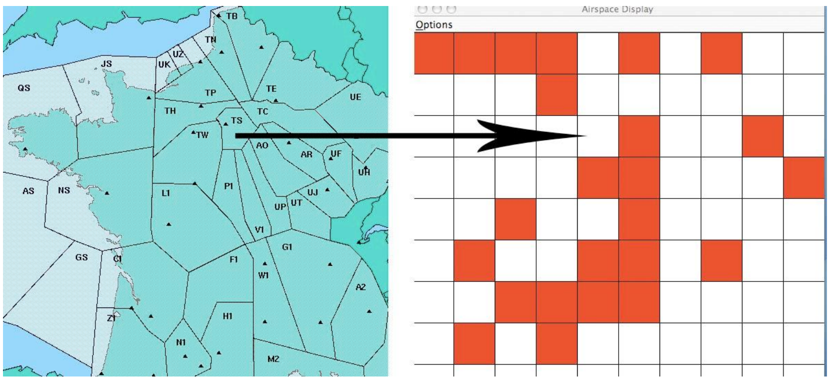
The multi-agents universe offers also an interesting ability to simulate the message exchange in communication networks (controller/controller communication and pilot/controller communication). These communications may represent information exchange, negotiation between the agents (collaborative decision making) or services exchange.

b. MULTI AGENT MODEL FOR CONGESTION DYNAMICS IN THE ENROUTE AIRSPACE

In the following, the physical model corresponds to the en route part of the controlled airspace. The mathematical model is represented by the objective correspondence between sectors and cells of a cellular automaton (Figure 2). The computational model corresponds to a multi agent system implementing the functions of the cellular automaton. Each sector is an environment agent integrating the operational rules of air traffic control. Similarly, each aircraft is a mobile agent following predetermined trajectory and communicating with sectors.

As seen in section 2, there is a significant difference between the planned traffic and the realized one [Gwiggner et al., 2006]. This difference leads to the congestion of a certain number of control sectors. In order to reduce the congestion and to keep a certain fluidity of the traffic, the controllers in the saturated sectors may reduce the speed of the aircraft or deviate from its trajectory to an available control sector. To be able to take into account these particularities of the ATC system, we integrated these aspects in the rules implemented in the cellular automaton where cells represent the controlled sectors.

Figure 2: Correspondence between sectors and sites



The algorithm for implementing air traffic control rules is as follows:

- Each sector is an agent modelling its behaviour of air traffic control in the operational context.
- The state of this binary valued agent: 0 if it is available (able to provide control service to an entering aircraft) and 1 if not (the sector is congested).
- An aircraft entering in sector s_a at time *t* is transferred to the following sector s_b according to the flight plan and the following rules :
  - at time $t + \Delta_a$ if s_b is available; where Δ_a is the needed time to cross the sector s_a;
    - if s_b is congested at time $t + \Delta_a$, the aircraft is delayed (by decreasing the speed) by one time unit, then transferred to sector s_b if s_b is available at time $t + \Delta_a + 1$;
- Otherwise, the aircraft is rerouted to one of the neighbouring and non-congested sectors with probability p_1.
- An aircraft may be subject to delays other than those imposed by sectors for security reason. That is why an aircraft may have randomly a delay while arriving to a sector with probability p_2 (this allows to take into account uncertainties related to the meteorological conditions, take-off delays, ...)
- The aircraft may increase its speed if it was already delayed with probability p_3.

c. SIMULATION OF THE MODEL

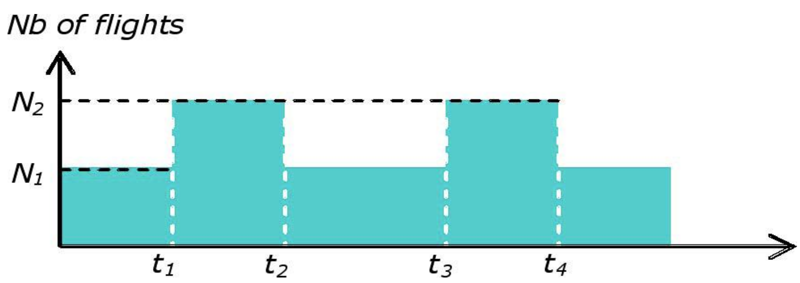
The model was implemented using Repast (Recursive Porous Agent Simulation Toolkit) [North et al., 2006]. A part of the controlled airspace, representing the en route part is modelled using a square grid of size *spaceSizeX*spaceSizeY*, each corresponds to a sector. The crossing time of sectors is uniformly distributed in *[minCrossingTime, maxCrossingTime].* The sector status is determined as follows:

- a sector *s* is available at time *t* if it contains a number of aircrafts inferior to its capacity *Cs* ; the maximum number of aircraft that a controller is able to manage simultaneously.
- sector capacities are distributed uniformly in *[min-Capacity,maxCapacity].*

Traffic pattern was generated randomly. The variable *nbPairsOrigDest* represents the number of origin-destination couples (*input-cell, output-cell*). The trajectory obtained is a segment having as extremities *Orig. cell* and *Dest. cell*. The flight plan generated is consequently composed of the list of sectors crossed by the segment. In order to take into account the fluctuation of the traffic during the day we used a particular distribution of flights where the traffic is doubled in two different time windows.

Let *nbFlights* = $\sum_{0}^{24} N_t$ be the total number of flight of the day (crossing the studied *en route* airspace). The distribution of the flights is introduced such that the traffic is doubled during the intervals (Figure 3): [t_1 = 6h; t_2 = 8h] and [t_3 = 18h; t_4 = 20h].

Figure 3 The distribution of the daily Traffic



The simulation shows the existence of a phase transition phenomenon concerning the congestion of the airspace due to a critical density of the traffic [Ben Amor et al., 2007]. For example, for a given parameterization we notice that while varying the number of flights we obtain a behaviour of the system totally different when a certain threshold is reached. In fact, for n < 50,000 (in particular for n = 30000 representing the mean volume of the daily traffic in Europe) and the other parameters being fixed according to the mean observed values in the real operational context, we obtain some local congestions that are quickly resorbed by the collaboration between sectors (Figure 4). When n ≈ 50,000, we can identify a phase transition phenomenon where the system is trapped in a situation where the congestion propagates through the whole area and local rules are unable to resorb this congestion (Figure 5). This phenomenon reflects situations where the system needs an external help to resorb the congestion (delaying take-off at the airports, change the routing plans for aircrafts on the ground, etc...)

Figure 4: The system absorbs the local congestion when *nbFlights* is inferior to the threshold

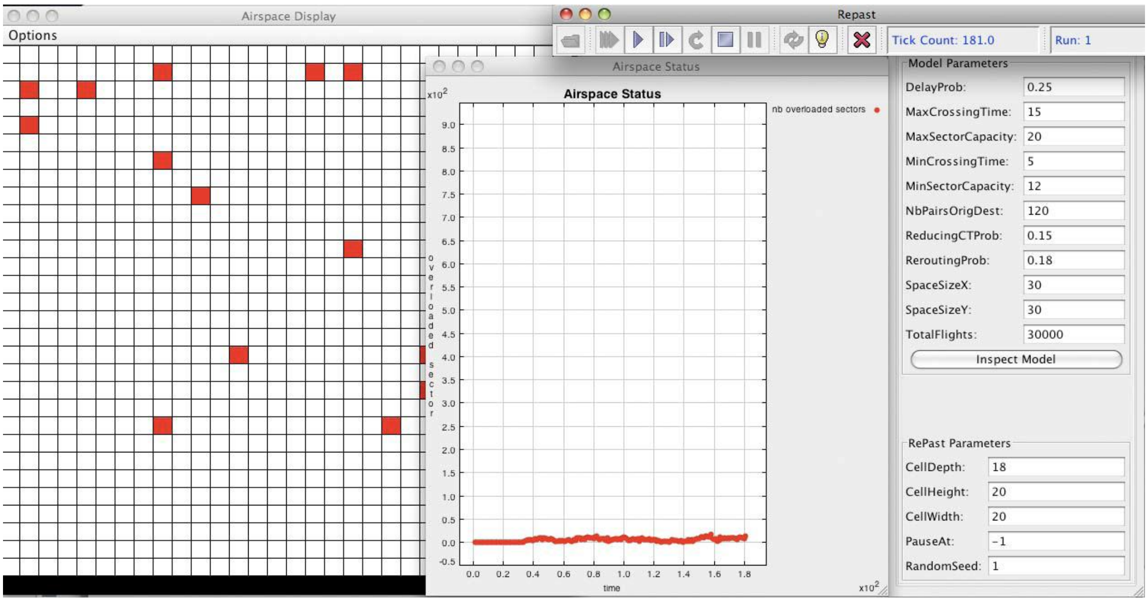
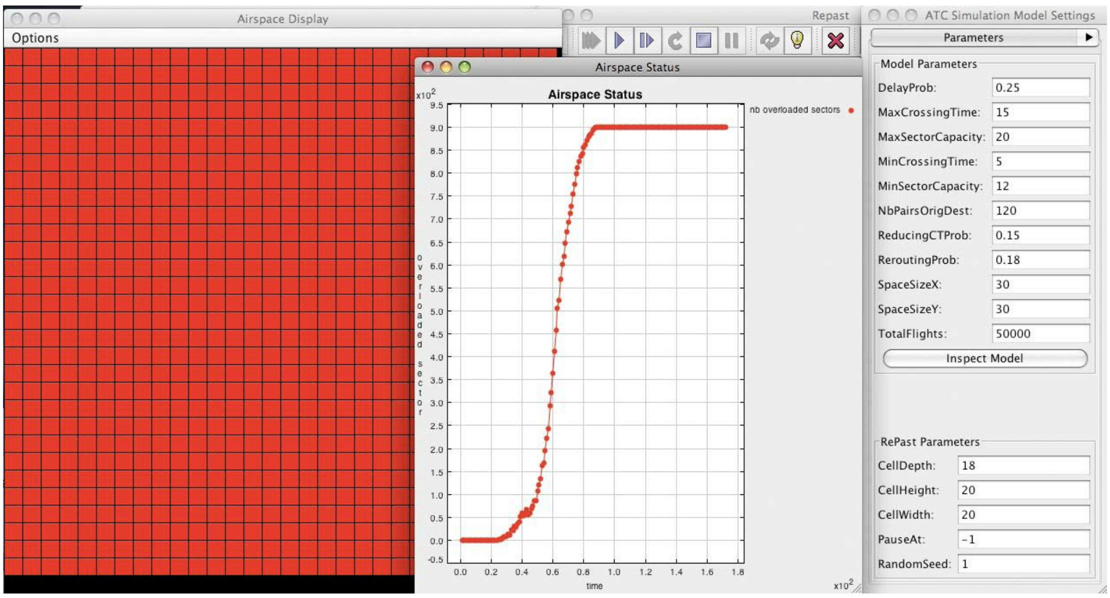


Figure 5: Phase transition phenomenon observed when the threshold of the parameter *nbFlights* is reached



4. VALIDATION WITH REAL DATA

In order to validate the model, from the qualitative point of view[4], we used the real data relative to a one-day traffic. To be useful we applied some treatments on these data in order to gather from different files the needed information implementing the model. We used in particular the following files:

- the file *ALL-FT.20070624*,traffic file of the CFMU giving the profile of all flight of the day (June 24th 2007). This file contains among other information the following parameters for each flight: departure and arrival airport, aircraft identity, company, type of aircraft, followed route, requested flight level, regulations (in particular rerouting), ATFM sent and received messages.
- the file *Airblock.296*, environment file of the CFMU giving the set of the elementary structural units of airspace, and their geographical coordinates.
- the file *Aircraft.296* giving for each aircraft its identity, type and performance.
- the file *Airport.296* containing the name, ICAO code and geographical coordinates of all airports in the world.
- the *Airspace.296* giving for each airspace entity its identity, name, type and the number of elementary sectors composing it.
- the file *Capacity.296* giving the capacity and specifying the type of the concerned element (control centre, elementary sector, composed sector...) and the time unit.
- the file *Configuration.296* giving for each control centre its configurations during the day and the name of the sectors in the different configurations.
- the file *Flow.296* giving the traffic flows existing between the different airports.
- the file *NavPoint.296* giving the number of beacons and for each its name, type and coordinates.
- the file *OpeningScheme.296* giving the opening schemes (merging and splitting of the sectors) of different control centres during the day.
- the file *routes.296* giving the available routes network during the day.
- the file *Sector.296* giving the number of the elementary sectors and for each its name and air blocks composing it.
- the file *TrafficVolume.296* dividing the traffic into traffic volumes and giving complementary information about the flows.
- the file *reroutingStats* giving statistics about the realized rerouting procedures.

[4] Correspondence concerning the simulated scenario and the realized traffic between the shape of the graphs giving the evolution of the number of congested sectors.

- the file *OverloadHourly* giving the total number of hours of congestion where the traffic exceeded the capacity by 1%, 20%, 40%, 60% et 80%. It provides also the different kind of regulation procedures realized to resorb the exceeding traffic.

In order to rebuild the realized traffic and represent the evolution of congestion level over time we need to elaborate a simulation scheme and manage the dependencies between the data contained in the different files. For example, the evolution of capacity depends on the opening schemes of the different centres which implies the reading of the file *OpeningScheme* and determine the structural entity to which the capacity is applied. Similarly, to determine the geographical location of a sector we need to open the file containing the list of *airblocks* composing it. More generally, the figure 6 gives the global map of dependencies between the different files. The figure 7, provides a general view of the simulation interface.

Figure 6 : File Dependencies Map

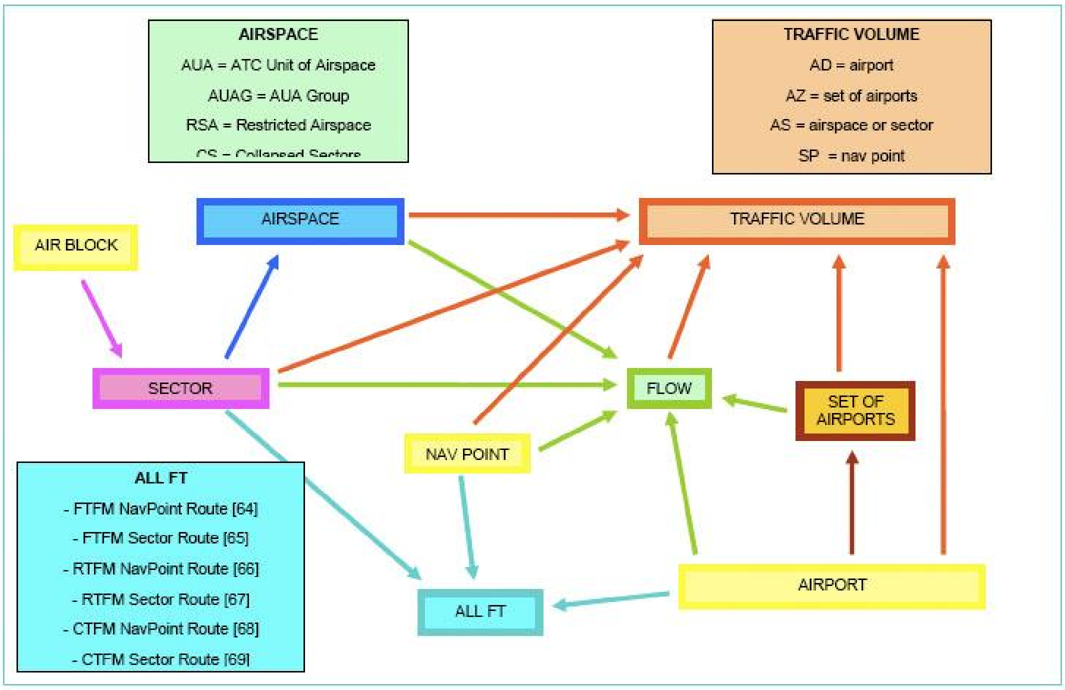
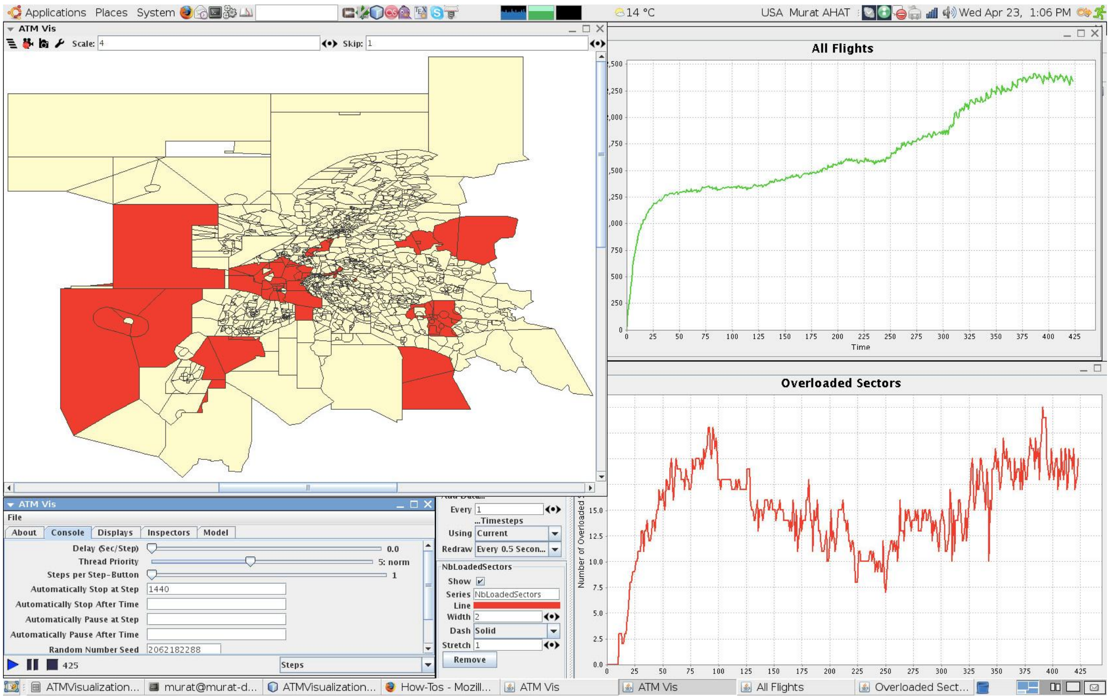


Figure 7: Evolution of the Congestion in the Airspace



The simulation using real data showed a similarity between the shape of the graph giving the observed congestion level of en route sectors in the European airspace (figure 9) and the graph given by the simulated scenario of the model using the following parameterization (figure 8) :

- probability of delay of aircraft on take-off : 0,25.
- capacity interval : [12-20].
- probability of regulation using speed : 0,15.
- sector crossing time interval : [5-15].
- rerouting probability : 0,18.

Nevertheless, even if the two graphs (observed and simulated congestion) are similar, they have mainly two differences:

- at the quantitative level, there is an important difference between the observed and the simulated congestion. By comparing the graph representing the evolution of the real number of congested sectors to the graph simulated congestion, we notice that the real congestion level is clearly inferior to the simulated congestion.
- the sharpness of certain peaks in the congestion are more important in the simulated

congestion.

The difference between the observed congestion and the simulated one is not surprising. Considering the sensitivity of the ATM system (as any complex system) to the initial conditions, the quantitative prediction is very hard to establish. The main objective of our model is essentially oriented to the reconstruction of congestion dynamics (the aspect of the congestion graph).

This quantitative difference may be explained also by the use of the instantaneous capacity (number of aircraft simultaneously present in the sector) and we do not integrate the hourly capacity (amount of the traffic that could be managed by a sector in one hour). Concerning the small differences in the peaks related the abrupt changes in the number of congested sectors we can provide these two elements of explanation:

1) the difference is basically due to the difference in the rerouting procedure used in the model compared to the real procedures. In fact, in the model we considered only the tactical rerouting but in the real operational context the flow managers using short term predictive tools are able to display specific online procedures to apply strategic rerouting schemes.

2) other real factors which are difficult to capture in the model may also provide a part of the explanation of this difference, e.g. the traffic management by controllers. Actually, controllers do not systematically apply a rerouting scheme when the sector is overloaded. It was shown by empirical studies that controllers are able to manage sometimes a certain traffic load which is more important than the declared theoretical capacity.

Despite these differences, our proposed model reproduced dynamics of the congestion which is very close to the real context. More, it allows testing hypothesis and different scenarios by varying the simulation parameters. Thus we noticed concordant observations with empirical studies. In particular, we tested the effects of the variation of the size of the sectors and noticed that there is a minimal size of sectors under which the propagation is amplified.

Figure 8: Simulated congestion - Traffic of June 24th 2007

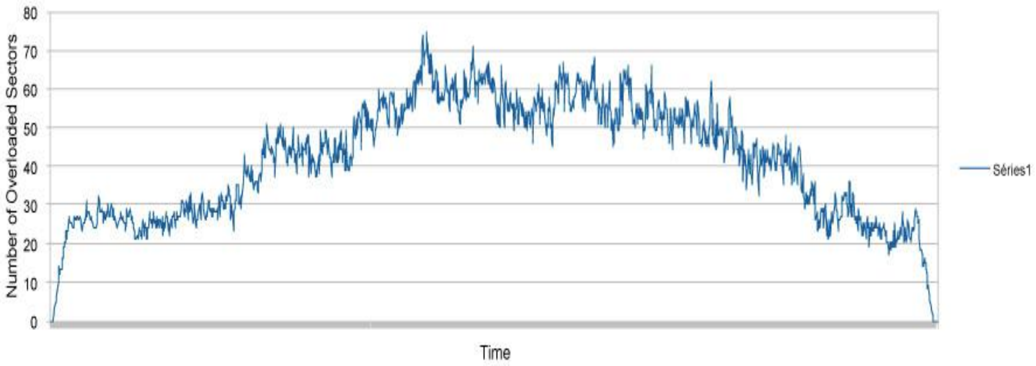
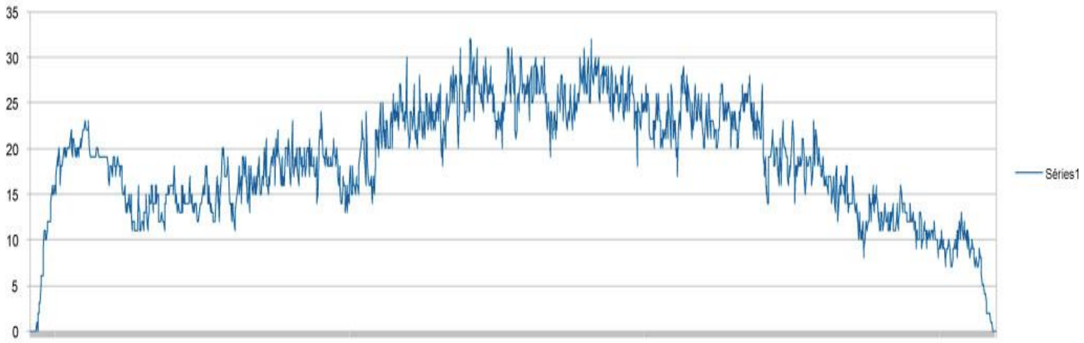


Figure 9: Observed congestion - Traffic of june 24th 2007



5. CONCLUSION AND FUTURE WORK

The systemic approach we used to model the dynamics of availability in ATC showed the complex nature of the behaviour of the system illustrated by the phase transition phenomenon which occurs when specific thresholds of key parameters (*i.e.* number of flights and crossing time) are reached.

Validation using real data of sectors shows the ability of the model to reproduce congestion dynamics similar to the real system. In a future work we aim to provide a mathematical model providing more precise quantitative predictions. To achieve this goal we need, from a mathematical point of view, to formalize and generalize the neighbourhood concept using pre-topology theory in order to express different kind of connections between sectors and to consider a more realistic neighbourhood basis.

Although airspace is a common resource, ATM in the European Union is still organised in a fragmented way. Every time a plane enters the airspace of a Member State, it is serviced by a different air navigation service provider on the basis of different rules and operational requirements. In order to improve capacity and efficiency while minimizing costs of air navigation services, European Member States provided a key mechanism integrated to Single European Sky (SES) and called Functional Airspace Blocs (FABs). This implies an operational organisation of airspace independently from country boundaries.

From a managerial and operational point of view, our model showed in particular the interest of the single sky and Functional Airspace Blocs (FABs) concepts. In fact, according to the simulations it is clear that a functional and operational segmentation of the controlled airspace is more efficient to guarantee a performing traffic management, by reducing conflicts due the heterogeneity of rules and operational requirements.

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