Investigating ATC Dynamics Using Random Cellular Automata

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Outline

Overview

Overall Context :

- **Complexity of ATM system**
  1. Societal Subsystem
  2. Technical Subsystem
  3. Human Subsystem
- **Heterogeneous interactions**

Goals :

- Complex systems modeling using appropriate theories
- Modeling ATM from a complex system point of view

Proposed model :

- A discrete model based on random cellular automata

Definition

Examples of complex systems definition

- *A complex system is a network composed of mutually interacting elements, where the global behaviour of the system can not be deduced from the sum of its components and their properties.*
- *Complex Systems is a new field of science studying how parts of a system give rise to the collective behavior of the system, and how the system interacts with its environment.* **[NECSI]**

Complex systems properties.

1. Emergence phenomenon
   - Appearance of new property in the system
2. Phase transition
   - Brutal change in the state of the system
3. Transition threshold
   - Critical value of a key parameter

Example of phase transition

Random graphs

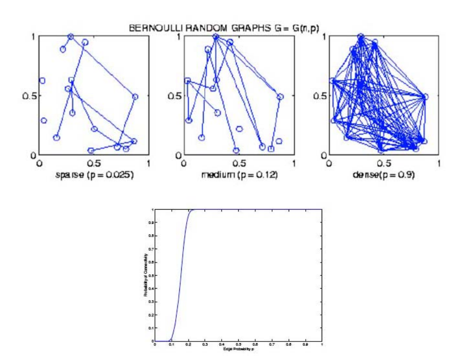


FIG.: The Bernoulli model.

Fundamental Questions

- How can we reconstruct multilevel dynamics from data, including bottom-up and top-down inter-level interactions ?
  - Reciprocity in the influences between individual parts and the whole system
  - Identification of levels of organization in complex systems (spatial and temporal scales)
- How can we study systems of systems ?
  - What are the specific emergent properties characterizing adaptive systems coevolving with changing environments ?
  - How do intra- and inter-systems links appear and disappear with changing strength ?

ATC complexity

The ATC subsystem is under supervision

- Airspace can be congested due to the difference between planned flights and realized ones.
- Human heteregeneous optimizing decisions introduce more uncertainty

Complexity aspects

- (1) Structural complexity (qualitative and topological properties of ATM system)
- (2) Dynamical complexity (time effect on the behavior and properties of the system)
- interaction (intricateness) between (1) and (2)

Structure

We showed the relation between the airspace structure and its dynamics. We concluded that :

- a homogeneous structure may be of some benefit on the fluidity of air traffic
- the time factor effects on the system dynamics
- controllers should have a more general information about the flight plans, in order to take into account the effects of their decisions on distant sectors

S. Ben Amor., M. Bui and I. Lavallée.
A Complex Systems Approach in ATM Modeling.
Paper presented at the ECCS'06. European Conference on Complex Systems, Oxford, 2006.

Dynamics : a top-down approach

- We showed the existence of a critical density of congested sites at which local optimization is no more efficient.
- The model is based on :
  - a global description of the random structure of the availability of sectors in the controlled airspace
  - a generic law giving the distribution of the difference between planned flights and realized ones.

S. Ben Amor., H. Tran Dac and M. Bui.
A percolation based model for ATC modeling and simulation.
6th International Conference of Research, Innovation and Vision of the Future Conference, February 2006. Ho Chi Minh City.

Recent results : a bottom-up approach

- We identified, similarly, the phase transition phenomenon by :
  - using the Random Cellular Automata formalism
  - implementing a multi-agent simulation approach
  - integrating local rules representing the real micro-level behavior (at the sectors scale level)

Cellular Automata

Cellular automata (CAs) are microscopic models for complex natural systems containing large numbers of simple identical components with local interactions. **[Wol84]**

They exemplify the fact that a collective behavior can emerge out of the sum of many, simply interacting components. **[Cho98]**

S. Wolfram.
Universality and complexity in cellular automata.
Physica D, 10 (1984).

B. Chopard, P. Luthi, and A. Masselot. .
Cellular automata and lattice boltzmann techniques : An approach to model and simulate complex systems.
Advances in Physics, 1998.

Sectors transposition into a square lattice

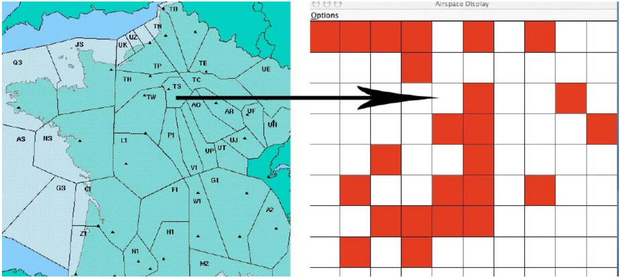
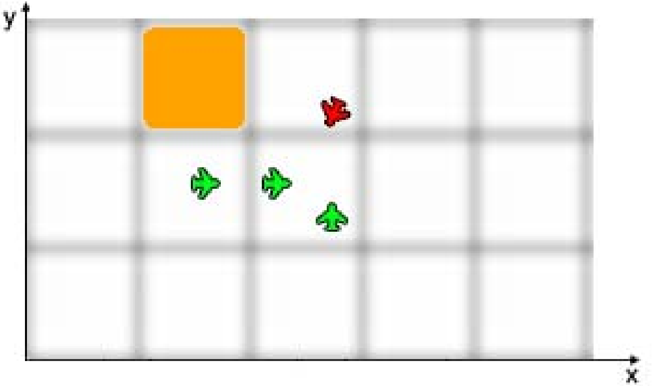


FIG.: Each sector is associated to a site in the square lattice.

Airspace congestion problem



The model

- Each controlled sector is an agent (automaton) which models the local behavior of the sector.
- A sector has two states : available if aircraft are still accepted into the sector. Otherwise it is unavailable.
- An aircraft entering in a sector s_a at the time t will be transferred to the next sector s_b in its flight plan :
  - At the moment $t + \Delta_a$ if s_b is available ; where Δ_a is the means crossing time of the sector s_a
  - If s_b is not available at $t + \Delta_a$, aircraft can be delayed for 1 time unit, and transferred to s_b if s_b is available at $t + \Delta_a + 1$
  - Otherwise, aircraft must be rerouted to one of the common neighbors sectors of s_a and s_b, with a probability of p_1

The model

- An aircraft can be delayed for 1 time unit with a probability of p_2 (as the consequence of potential conflict resolution, bad weather, ...)
- An aircraft can reduce the crossing time in a sector, if it was delayed, with a probability of p_3

Implementation

- Implemented with Repast (Recursive Porous Agent Simulation Toolkit)
- Mean crossing times of sectors are distributed uniformly in [minCrossingTime, maxCrossingTime]
- State of sectors : a sector s is available at a moment t if the number of aircrafts does not exceed its capacity C_s.
- The sectors capacities in our implementation are distributed uniformly in [minCapacity,maxCapacity].

Implementation : Traffic pattern

- **nbPairsOrigDest** is the number of pairs of $input - cell$, $output - cell$ which represent entry and an exit points of the airspace portion, distributed uniformly at random. The shortest path from Orig. cell to Dest. cell is found, giving the list of cells which a flight cross.
- **nbFlights** is the total number of flights crossing the airspace in a days.

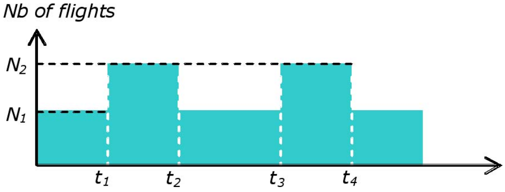


FIG.: The distribution of flight insertion in the system.

Simulation : Resorption

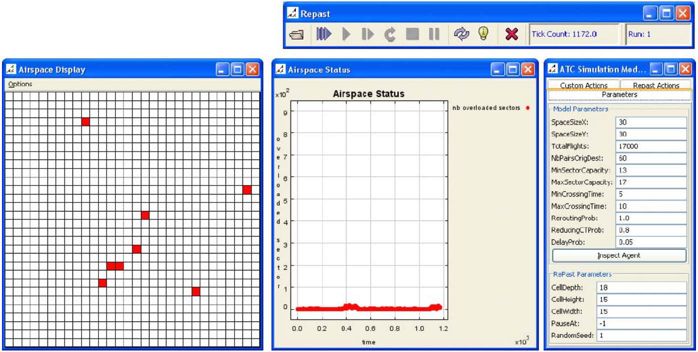


FIG.: The system absorbs local congestion when *nbFlights* is inferior to the threshold.

Simulation : Phase Transition

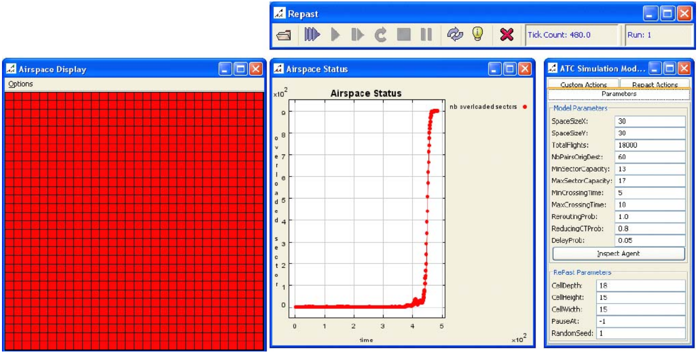


FIG.: Phase transition phenomenon observed when the threshold of the parameter *nbFlights is reached.*

Conclusion and future work

This model shows

- A model simulating the propagation of airspace congestion
- It exhibits network effects of sector's saturation.
- Phase transition phenomenon is identified
- The analysis of the phenomenon can help us to study the reliability of the system

Future work

- Interpret the real data using multi-estimation
- Take into account the ATFM regulation effects.