Project no: 043268

Project acronym: PATRES

PATTERN RESILIENCE

Publishable final activity report

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Project coordinator: Guillaume DEFFUANT

Project coordinator organisation: Cemagref Revision: Version 1

Scientific problem and objectives

The project chose to found its research on Martin's (2004) formalisation of the concept of resilience, which is based on viability theory. This framework is more general than existing definitions because it requires no assumption about the dynamical properties of the system. Moreover, the approach enables to compute laws of actions on the system in order to keep or restore a desired property, lost after a perturbation.

However, solving a viability problem is practically possible only when the problem is expressed in state space of relatively small dimensionality (up to 7 or 8 dimensions). It is therefore impossible to apply the method on systems described by a large number of interconnected entities, because the state space has too many dimensions. Nevertheless, when the interconnected entities generate statistical regularities or patterns, which can be described with a reasonable number of dimensions, and when the desired properties of the system are related to these patterns, the approach can be adapted. The association of patterns with resilience justifies the title of the project: *"pattern resilience"*.

The main objective of the project derives from this scientific challenge: to elaborate efficient methods and tools for modelling and managing pattern resilience in complex systems. The methods integrate contributions from the research on resilience, more particularly its link with viability theory, and methods for pattern identification in models and data.

The main objective therefore includes two aspects:

- *Defining more powerful and more flexible methods and tools for solving viability problems* than current ones, in particular using recent statistical tools such as Support Vector Machines (SVMs), and therefore increase the range of systems in which the resilience problem can be solved.
- *Providing a set of methods and tools for modelling pattern dynamics*, building on current work on the exploration of models with systematic experimental designs, and on general statistical physics approaches.

The project investigates the efficiency of the developed methods and tools on *four case studies*, in very different domains (ecology, social sciences, cognition).

Participants

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2	University of Surrey Department of Sociology	UniS	UK
3	Universitat Illes Balear IFISC	UIB	S
4	Helmholtz Centre for Environmental Research - UFZ Department of Ecological Modelling	UFZ	D
5	Centre National de la Recherche Scientifique Centre de Recherche en Epistémologie Appliquée	CNRS	F

Work performed

The work included the development of general methods and tools, and their test on a set of case studies. This development has been progressive, with pilot versions of the tools and case studies in the first period of the project, and more refined versions in the second phase. The work included mainly the derivation of new methods inspired from mathematics and physics, the development of computer tools and models, the extensive test of the tools on different models and writing scientific articles. Moreover, for some case studies, new tools for collecting data were developed.

This work was carried out through several collaborations between the consortium teams, in particular between specialists of some methodologies (pattern dynamics, viability) and specialists of one case study. To manage these collaborations, five plenary meetings and seven visits between partners took place.

Moreover, we organised two knowledge dissemination workshops:

- a one day presentation in a satellite workshop of the European Conference on Complex Systems in Warwick,
- a three day course for young scientists, which was held in Madeira.

The main dissemination vector for the future is the book produced by the consortium. It describes in details the methods and tools, as well as their applications on case studies. It will be published by the end of 2010.

Results achieved

Extending current definitions of resilience toward an action oriented approach

During the project, we improved collectively the formal definition of resilience based on viability, and we identified better its links with existing definitions. In particular, we considered the main existing formal definitions of resilience: one based on a linearization of the dynamics in the vicinity of an attractor of the dynamics, often called the "engineering resilience", and another one based on regime shifts and attraction basins size. We showed that these definitions can be seen as particular cases of the viability based definition, which is therefore more general. We illustrated this claim on an example from the literature (Anderies et al. 2003). Moreover, we showed that the viability based resilience is more action oriented, because one can compute policies of action to maintain or drive back a system into a desired state set in its framework.

Practically, we suppose that the system is defined with differential equations, with a variable representing the action on the system. Choosing different values of this variable modifies the system's trajectory. Moreover, we suppose that the users of the system are able to define a subset of the state space corresponding to the desired behaviour of the system (for instance, a minimum level of grass biomass in savanna). The problem becomes to keep the system in the set of desired states, or if it out of it for any reason, to drive the system back to it and keep it there. The states from which there exists a policy of action maintaining the system indefinitely inside the desired set are called "*viable states*", the states from which there exists an action policy leading to a viable state are called "*resilient states*". Hence in this approach, resilience supposes that viability is defined.

We are conscious that this definition has no chance to replace less formal views of resilience which have their own interest as "intermediate objects" favouring interdisciplinary work. But we claim that the viability-based definition can be a fruitful reference for these less formal views, and it can have a practical interest by proposing policies of action when a formal model of the considered system is available.

Pattern resilience: a general approach tested on a set of case studies

The main problem of the practical application of the viability-based resilience is that the computation of viable or resilient states is very heavy computationally. In particular, it is impossible to apply it directly to systems defined in a state space with many dimensions. For instance, the models including interacting agents include a lot of variables defining their states, and hence the computation of viability-based resilience in such systems appears out of current computational means.

However, we prove on several case studies that it is sometimes possible to approximate the main pattern dynamics of the system, using more synthetic representations, and then to compute the viability and resilience on the approximated dynamics. The general approach includes the following steps:

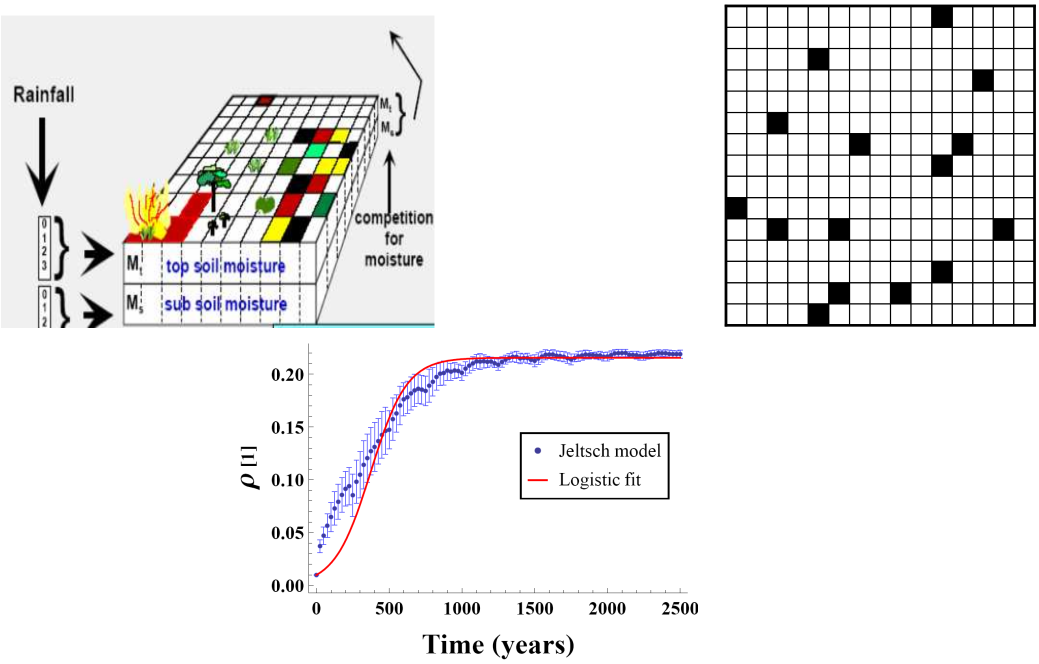

Fig. 1: Savanna case study, first step: the complex model (top left) is simplified into a cellular automaton (top right, black squares are trees, white squares are grass), with rules derived from simple functions fitting the simulations of the complex model (bottom).

- define a simpler individual based model, with simplified individuals and dynamics (see fig. 1),
- to apply methods of statistical physics (such as pair approximation) on this simplified model, yielding synthetic representations of the system's pattern dynamics,
- to define the desired state set in the state space of the pattern dynamics,
- to compute viability and resilience of the system relatively to this desired state set, and corresponding policies of action (see fig. 2).

In this approach, it is necessary to make many computation experiments: first to check that the simpler individual based model (IBM) fits well the more complex one, and then to check that the synthetic pattern dynamics model fits well the simpler IBM. It is also important to perform sensitivity analyses of these models, and to explore their regime shifts.

In most cases, it is also interesting to perform a sensitivity analysis of viability and resilience when the parameters of the model vary. This provides the values of the parameters for which the system has the highest viability or resilience. Moreover, we tested the typical optimal policies provided by the software for different values of the parameters.

$$
\begin{aligned}
\frac{d\rho[1]}{dt} &= \beta\left(z_n q_n[1/0] + z_f q_f[1/0]\right)(1-\rho[1]) \\
&\quad \times P_F^{Surv} e^{-\delta z_n q_n[1/0]} - \alpha\rho[1] \\
\frac{1}{2}\frac{d\rho_n[11]}{dt} &= \beta\left(1 + (z_n - 1)q_n[1/0] + z_f q_f[1/0]\right)(\rho[1] - \rho_n[11]) \\
&\quad \times P_F^{Surv} e^{-\delta(1+(z_n-1)q_n[1/0])} - \alpha\rho_n[11] \\
\frac{1}{2}\frac{d\rho_f[11]}{dt} &= \beta\left(z_n q_n[1/0] + 1 + (z_f - 1)q_f[1/0]\right)(\rho[1] - \rho_f[11]) \\
&\quad \times P_F^{Surv} e^{-\delta z_n q_n[1/0]} - \alpha\rho_f[11],
\end{aligned}
$$

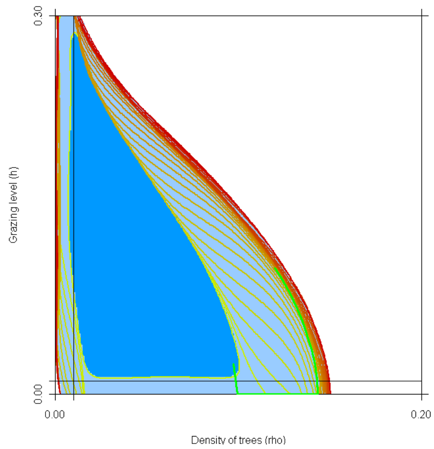

Fig. 2: Left: differential equation defining pattern dynamics from the simple model of savanna. Right: representation of viability kernel (in blue), resilience indices (lines from yellow to red) and trajectory of the system returning to the viability kernel after perturbation (in green).

In addition to this general approach, the work on the case studies achieved some noticeable results:

- In the savanna case study, we showed that the interaction between tree-tree establishment competition and fire is fundamental to explaining savanna dynamics. Moreover, we identified specific management strategies for maintaining the savanna in a desired state set.
- In the bacteria case study, we identified a new realistic mechanism for generating observed patterns in bacteria populations (see fig. 3). Moreover, in an idealised setting, we derived policies of actions for maintaining the characteristics of these emergent patterns.
- In the language competition case study, we proposed a more comprehensive analytical model which includes the stochastic part of the dynamics. Moreover, on simpler versions of this model, we computed policies of action on the prestige of languages in order to keep their diversity.
- In the social dilemma case study, we used a toy model of interacting agents with more or less cooperative behaviours, and we derived from it policies of actions for a public body to favour cooperative behaviours.
- We gathered new sets of data about the web 2.0, and observed patterns for the evolutions of wikis and sites for sharing images (Flickr).

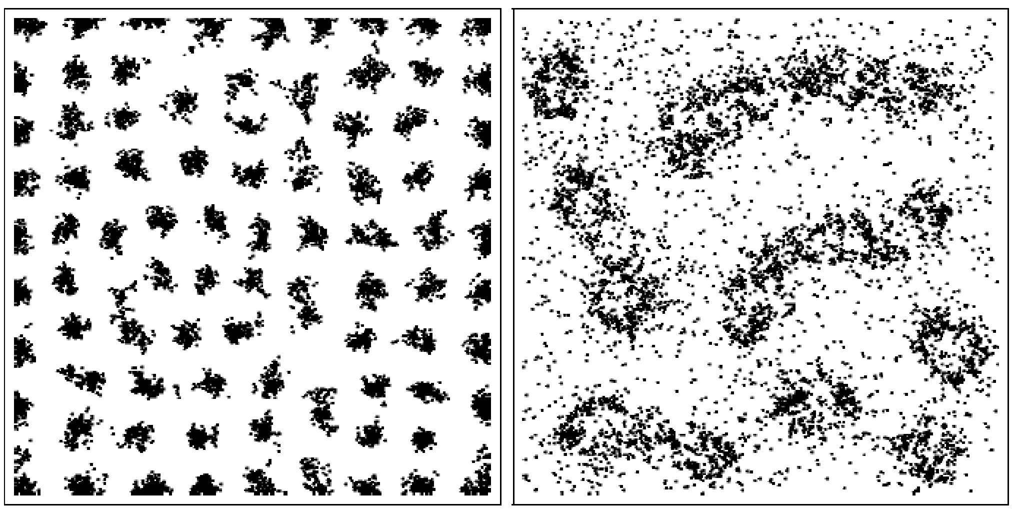

Fig. 3: Example of patterns obtained from the bacteria model, obtained by changing the value of one parameter. The challenge was to maintain some of their characteristics through adequate actions.

KAVIAR a general tool for computing viability and resilience

The project developed a prototype software tool for computing viability kernels and resilience indices (see its interface on fig.4).

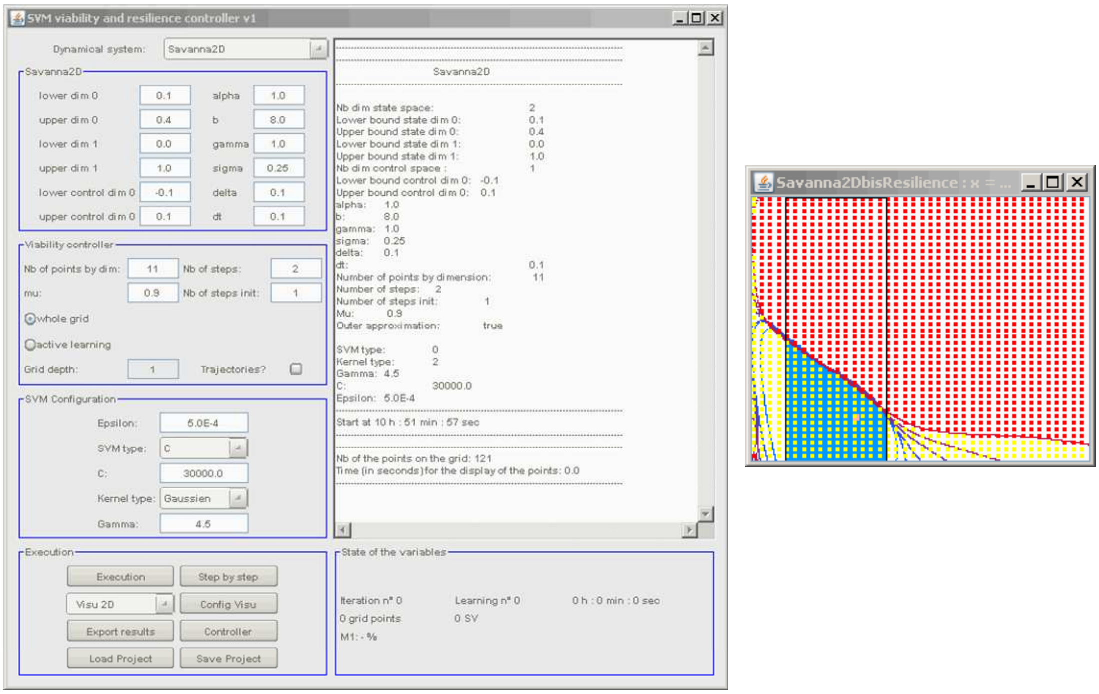

Fig 4: User Interface of KAVIAR

This software includes recent advances on viability kernel approximation with "support vector machines" (SVM). In its simplest version, the algorithm uses a lattice defined on the state space. Then an algorithm defines iteratively a training set separating viable from non-viable points with respect to the current approximation. SVMs are well known for providing efficient and parsimonious solutions to such problems. More sophisticated versions of the algorithm, using only a part of the lattice for learning ("active learning") are also implemented. Then, the software provides the control policies to apply in order to remain in the viability kernel, or to drive the system back into it. A specific variant, optimised for the computation of resilience indices, is also available.

We wrote a user guide for this tool, and several participants of the project were trained to use it on their problems. The software is available from the project web site: http://www.patres-project.eu.

SimExplorer, a software tool supporting complex simulation experiments

When one wants to identify patterns in models, repeating heavy simulation experiments is often necessary. The prototype software of SimExplorer, developed during the project, helps the user to define a workflow for such experiments: experimental design, generation of model inputs, model launching, model outputs treatments (see fig.5). It includes a link to commonly used libraries to define experimental designs and statistical treatments (R packages), facilities to trace the experiments and manage their quality, facilities to launch experiments on computer clusters or grids. The development of this tool has also been financially supported by LifeGrid program (until September 2008). We used the software on some of the case studies (in particular savanna and bacteria).

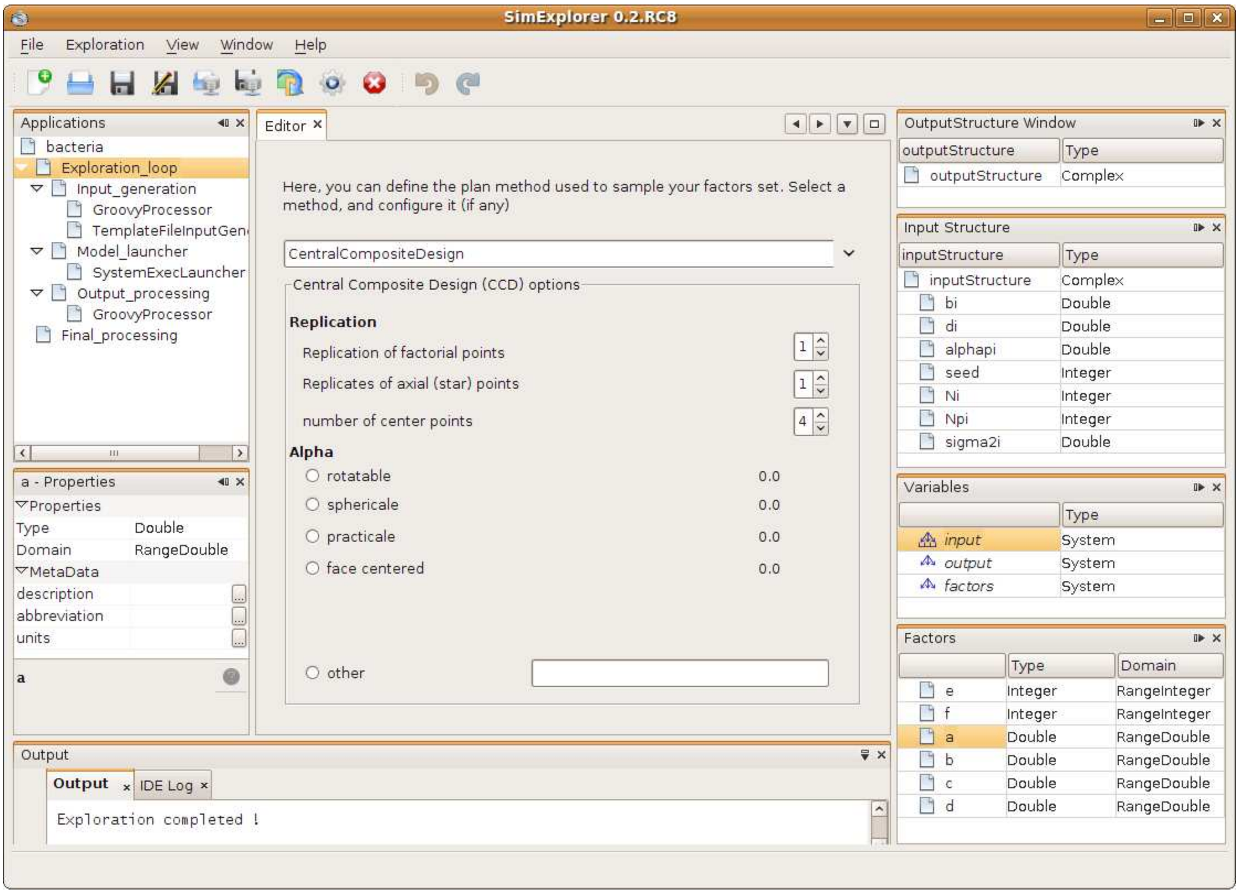

Fig. 5: User interface of SimExplorer.

Dissemination and use

No economically exploitable knowledge was identified at the end of the project.

In addition to the dissemination actions that we took during the project, the main vectors for dissemination of knowledge for the future are:

- The project website which includes the main publications and the links to the software sites.
- The websites with the software tools: SimExplorer and KAVIAR, from where the software and documentation are downloadable.
- The book, to be published by Springer, which presents the methods and the results of the project on the case studies (it one of the deliverables).