# VIABILITY AND RESILIENCE OF COMPLEX SYSTEMS

# VIABILITY AND RESILIENCE OF COMPLEX SYSTEMS
## Concepts, Methods and Case Studies from Ecology and Society

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**Kluwer Academic Publishers**
Boston/Dordrecht/London

# Preface

This book is based on the research carried out during the PATRES (Pattern resilience) project, supported by the European Commission as part of its 6th Framework Programme. The project involved five European research teams, specialising in methods (computer science, applied mathematics, the physics of complex systems), and in the broad areas of application of the research: ecology and sociology.

The central concept of the book is resilience. This concept is having an impact in a wide variety of fields, such as ecology, sociology and psychology. Some people consider it to be key for designing and implementing a truly sustainable future. The basic idea behind resilience is the ability of a system to recover after strong perturbations. But when it comes to the details, there is much discussion among scientists and specialists. Mathematical definitions have the advantage of being precise and unambiguous, but they are criticised as too narrow. Fuzzier, more verbal definitions have a richness of meaning and may play a role as boundary concepts between different disciplines, facilitating exchange between them but they are not directly operational.

Our first motivation is to contribute to this debate. The initial challenge of the project was to build on a recent formalisation of the concept of resilience, based on viability theory (Martin, 2004). This definition is founded on a precisely defined mathematical theory and is, in our view, closer to the intuitive concept than other existing mathematical definitions of resilience. Moreover, the viability based definition is oriented towards action on the system: it allows one to compute laws of actions on the system in order to keep or restore a desired property, lost after a perturbation. General algorithms for doing such computations exist.

However, solving a viability problem is in practice possible only when the problem is expressed in a state space of relatively small dimensionality (up to 7 or 8 dimensions). It is therefore impossible to apply the method to 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 that can be described in a reasonable number of dimensions, and when the desired properties of the system are related to these patterns, the approach can be used. The association of patterns with resilience justified the title of the project.

The main objective of the project was derived 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 had two aspects:

- Defining more powerful and more flexible methods and tools for solving viability problems, using recent statistical tools such as Support Vector Machines (SVMs), in order to increase the range of systems for 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. These methods and tools were tested on case studies, drawn from very different domains in ecology and the social sciences.

In the first part of the book, we introduce the concepts of resilience and viability.

The first chapter is a short introduction to the literature about resilience, concluding with the main challenges faced at the state of the art. We discuss the necessity of coining a definition that is neutral about the properties that the system should maintain. Choosing such properties implies that we have *a priori* values about what the system should or should not do. The choice of these values belongs to morals, politics, or business, not to science, although as scientists we can make an important contribution by identifying what options are available and whether any of them imply unrealisable outcomes.

The second chapter presents the viability based definition of resilience using an example, and compares it with more usual definitions. This chapter also introduces the main concepts of viability theory: the viability kernel and capture basin. It shows that the viability based definition is a generalisation of the so-called 'engineering' definition of resilience and also of other definitions based on attraction domains.

Then, in the second part, we test the approach on a set of case studies, which all start with an individual based model, defined by a population of interacting agents. Such dynamics have far too many variables to be compatible with the current tools for computing viability kernels and capture basins. Therefore, an important question addressed in the book is how to describe a complex dynamics using only a small set of synthetic variables.

The first case study is devoted to a model of competition between languages that is, for some values of its parameters, equivalent to a well known model of behaviour propagation, the voter model. This model is used to illustrate different techniques coming from physics for deriving synthetic dynamics from the individual interactions, and we show how viability based resilience can be computed for the case of the mean-field approach. We suppose that it is desirable to retain at least a minimum number of speakers of all the existing languages, and that an institution has some means of modifying the prestige of the languages.

In the case study on collaborative Web communities, we start by reviewing conceptual and empirical issues in the identification of desirable viable states for these systems. We present a summary of empirical analyses of their dynamics, focussing on two paradigmatic cases: peer production systems and social media groups. A simple model is then proposed in which the viability of these systems is assessed against constraints on group population and group content size. We discuss the interaction of these constraints, the autonomous demographic dynamics of such systems and the possible control actions which may be adopted to ensure or restore their viability.

In the savanna case study, we consider first a quite detailed model of the ecological dynamics, including a large number of variables, distributed over a set of spatial components. In this case, we first had to derive a simpler individual based model to be able to obtain a sound synthetic dynamics. It was necessary in this case to keep some indicators of the spatial pattern, using pair correlation in addition to mean field equations. After having described this simpler model, we consider the problem of maintaining the savanna through actions modifying the grazing level.

In the bacteria biofilm case study, we also start with a complex individual based model that we first simplify. In this case study, we again use a pair approximation approach to get synthetic information about the spatial pattern. However, instead of considering this information at two specific distances, as in the savanna case study, we derive a more global indicator for the shape of the pair approximation function. Then, the resilience problem that we address is to keep a particular spatial organization of the biofilm, together with bounds on the density of bacteria.

In the third part of the book, we describe in more detail tools and techniques used in the case studies.

We first describe Kaviar, a software prototype that computes viability kernels and capture basins that was developed during the project. It uses a learning technique known as support vector machines (SVMs). The chapter explains how learning techniques in general, and SVMs in particular, can be used to facilitate the computation of viability kernels and capture basins. The chapter also provides practical examples that are complementary to the software user guide.

The final chapter of the book describes how viability and resilience can be used to derive more robust policies of action. The idea is to compute the distance to the boundary of the viability kernel, and to define the action that keeps the system as far as possible from this boundary.

The research reported in this book has been carried out with the support of the European Commission through a Sixth Framework Programme European project (NEST-Complexity, number: 043268, acronym: PATRES) for which we are grateful.

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