Nonlinear Systems and Complexity

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Mohamed Nemiche
Mohammad Essaaidi *Editors*

Advances in Complex Societal, Environmental and Engineered Systems

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Mohamed Nemiche • Mohammad Essaaidi
Editors

Advances in Complex Societal, Environmental and Engineered Systems

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Editors
Mohamed Nemiche
Ibn Zohr University
Agadir, Morocco

Mohammad Essaaidi
ENSIAS College of Engineering
Mohamed V University of Rabat
Rabat, Morocco

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Preface

This book addresses recent technological progress that has led to an increased complexity in societal, ecological, and engineered systems. This complexity is characterized by the emergence of new proprieties and structures resulting from nonlinear interactions among system elements and between system and its environment. This volume provides researchers and managers with qualitative and quantitative methods, bottom-up and holistic approaches for handling many features of the complex contemporary reality. This book is composed of three parts with a total of 13 chapters: Part I (Chaps. 1–6) focuses on societal and ecological systems, Part II (Chaps. 7–12) deals with approaches for understanding, modeling, forecasting, and mastering complex systems, and Part III (Chap. 13) includes real-life examples. Each chapter of this book has its own special features; it is a self-contained contribution of researchers working in different fields of science and technology relevant to the study of complex systems including Agent-Based Modeling, General Systems Theory, and Mathematical Modeling.

In the chapter "ProtestLab: A Computational Laboratory for Studying Street Protests," Lemos, Coelho, and Lopes present an Agent-Based model for the simulation of street protests, with multiple types of agents (protesters, police, and "media") and scenario features (attraction points, obstacles, and entrances/exits). In this model agents can have multiple "personalities," goals, and possible states. The model includes quantitative measures of emergent crowd patterns, protest intensity, police effectiveness, and potential "news impact," which can be used to compare simulation outputs with estimates from videos of real protests for parameterization and validation. ProtestLab was applied to a scenario of policemen defending a government building from protesters and reproduced many features observed in real events, such as clustering of "active" and "violent" protesters, formation of moving confrontation lines, occasional fights and arrests, "media" agents wiggling around "hot spots," and policemen with defensive or offensive behavior.

In the chapter "A Generic Agent Based Model of Historical Social Behavior Change," Ahmed M'hamdi et al. describe and discuss how human societies change over time. The main objective of this work is to build a generic agent-based model of artificial social evolution in order to explore the East–West and North–South divides, the migration process, and some possible evolution ways.

In the chapter “Understanding Social Systems Research,” Klein embarks on the challenge of social complexity. He illustrates how decomposing our notion of the social into political and cultural aspects improves our possibilities to understand social systems. The praxeological departure point of the chapter is the reception of the volatile, uncertain, complex, and ambiguous (VUCA) world in project management. Referring to the works of Niklas Luhmann the importance of meaning creation and sensemaking for social systems comes into sight. Leading from Systemic Inquiry to Systems Analytics, Klein describes the state of the art of social systems research and the implications for problem structuring and research design. Klein ends on a reflection on the necessity of systems literacy and social design impact evaluation as a way forward for the twenty-first century to become systems savvy.

In the chapter “ForestSim: An Agent-Based Simulation for Bioenergy Sustainability Assessment,” Mark Rouleau proposes the use of Agent-Based Modeling (ABM) for bioenergy sustainability assessment. His study focuses on the assessment of second generation bioenergy from woody biomass as a potential renewable energy alternative to fossil fuels. He uses ForestSim, an ABM simulation to assess the sustainability of bioenergy development in the heavily forested region of the Upper Peninsula of Michigan, USA. He explains how ABM makes it possible to investigate bioenergy sustainability as a complex phenomenon that emerges within a coupled human and natural system. He compares the ABM simulation approach to conventional Life Cycle Assessment and explains why ABM is necessary to understand the complex dynamics of a bioenergy system. Finally, he compares his approach to an existing sustainability study in the UP with the goal of estimating biomass availability within the context of economic viability, ecological balance, and the social acceptance of bioenergy. He believes that his approach offers valuable insight into bioenergy sustainability and provides an important alternative assessment method.

In the chapter “Toward a Complex Concept of Sustainability,” Humberto Mariotti examines the relationships between complexity theory and some situations not usually approached in the pertinent literature. One of the studied aspects is the need to insert human nature among the variables of the sustainability/complexity relationships as a way to “complexify” them, as well as to provide a kind of realism that is badly needed to work on complex issues. The complexity of human nature is studied from several perspectives. The chapter is closed with the presentation of what the author calls a complex concept of complexity.

In the chapter “Effects of Policy Decision-Making on Riparian Corridors in a Semi-Arid Desert: A Modeling Approach,” Pope and Gimblett project the impact of an urban community on vegetation along the Upper San Pedro River. The riparian corridor is highly valued as important habitat in the American Southwest; nearly 57,000 acres of public land in the watershed are protected by Congress as a Riparian National Conservation Area. However, the corridor is at risk from extensive groundwater pumping to satiate growing urban demand. This work was designed to produce the potential effects of policy decision-making on riparian vegetation, including how much, where, and the likelihood of change occurring. A model was developed that combined both agent-based and Bayesian modeling techniques with three submodels: social, hydrological, and ecological. Using a variety of policy scenarios, the agent-based model predicted the percent change in vegetation area as well as the area the change is likely to occur while the Bayesian model produced likelihoods of change. The models were developed to be stakeholder-friendly, so that local decision-makers could use them to help make better decisions.

In the chapter "Dialectical Systems Theory as a Way to Handle Complex Systems," Matjaz Mulej et al. explain that complexity in natural, social, organizational, and technological phenomenon is hardly to be handled by the specialist vision unless one applies one or more of the versions of systems theory, which support interdisciplinary creative cooperation, such as the Dialectical Systems Theory. They also demonstrate that the related applied methodologies and methods are also very useful, because they can be used without too much complexity of theories, such as "Corporate Social Responsibility" (ISO 26000), "USOMID," "Six Thinking Hats" and their synergetic applications.

In the chapter "Reducing Complexity of Nonlinear Dynamic Systems," Nagy-Kiss et al. present a systematic procedure to transform a nonlinear system into a polytopic one without causing any information loss, contrarily to most existing studies in the field. They also present a robust observer synthesis with respect to internal/external perturbations, modeling parameterization errors, and unknown inputs for the estimation of the state variables. The above-mentioned points are applied to an activated sludge wastewater treatment plant, which is a complex chemical and biological process.

In his chapter "A Few Reflections on the Quality of Emergence in Complex Collective Systems," Vincenzo De Florio discusses the major factors that play a role in the persistence of emergence in collective systems. By means of those factors, a "general systems theory" of emergent systems is proposed. Several classes of emergent systems are then exemplified, ranging from simple aggregations of simple parts up to complex organizations of complex collective systems. The chapter also discusses the relationship between quality of emergence and resilience, namely the persistence of system identity. As suggested already by G. W. Leibniz, De Florio argues here that emergence and its quality may be better assessed by considering the interplay between intrinsic, extrinsic, and "social" aspects.

In the chapter "Link Structure Analysis of Urban Street Networks for Delineating Traffic Impact Areas," Wen et al. propose an innovative analytical procedure of ranking algorithm, the Flow-based PageRank (FBPR), for investigating the traffic flow concentration, complexity of street network structure, and traffic impact areas. A network modularity algorithm is used for delineating the traffic impact areas that will be affected by traffic congestion. The results indicate, by overlapping the topological structure of street network and flow concentration, street segments prone to traffic congestion are identified, including the Central Business Districts (CBD), and the areas proximate to the stations of the combination of MRT and train railway systems. Meanwhile, the delineation of traffic impact areas could be spatially targeted at priorities of traffic improvement for city planners.

In the chapter “Logic, Mathematics and Consistency in Literature: Searching for Don Quixote’s Place,” Montero et al. combine fuzzy logic with other techniques to analyze the consistency of the linguistic discourse about the village Miguel de Cervantes (1547–1616) decided not to reveal in his classical Don Quixote’s novel. In particular, the authors consider Cervantes linguistic description of Don Quixote’s trips from and to that place in order to check if such information is consistent with the map of La Mancha, and allowing a more or less constant walking speed march per day. From this complex system of information, it is then concluded that there is in fact a small region in the center of Campo de Montiel that meets all estimated walking times per day, showing that Cervantes linguistic description of the trips involving the hidden place is in this sense consistent.

In the chapter “Energy-Efficient Buildings as Socio-Technical Complex Systems: Approaches and Challenges,” Lachhab et al. present important metrics that assess performance and occupants’ comfort in energy-efficient buildings and study their relationships with building physical properties, equipment control, outdoor environment, and occupants’ behavior and activities. The authors analyze occupants’ actions and behaviors in context taking into account the complex interlinked entities, situations, processes, and their dynamics. Lachhab et al. then review existing control approaches and solutions for energy efficiency in complex buildings. They highlight simulation tools that aim to study and analyze approaches for energy consumption, occupants’ comfort, and CO_2 emissions. They also introduce their ongoing work related to modeling and control of these complex systems by highlighting the necessity of the development of intelligent building management systems that could include run-time processing techniques of large amount of data for deploying context-aware event-triggered control techniques.

In the chapter “Modeling Space-Time-Action Modularity and Evolution of Living Systems,” Pierre Bricage develops a new paradigm of “the gauge invariance of living systems” which allows him to define functionally and dynamically the hierarchical fractal organization of all living systems, from the quantum of Planck to the whole universe. The ontogeny of interactions and the interaction of ontogenies are topologically related through a power law of exponent 3/2, which is basically related to the Brownian motion. His work was motivated by the need to understand why all living systems are emerging through juxtaposition and embedment of previous ones in a new blueprint that is always an Association for the Reciprocal and Mutual Sharing of Advantages and Disadvantages: “interaction is construction and construction is interaction” both for the spaces and times, which are juxtaposed and embedded simultaneously into limited spatial and temporal networks, within an “independent of mass-entropy relationship inter-active optimal surface flow of flows” organizing control.

The editors would like to thank all the authors who contributed to this book. Special thanks also go to Mr. Christopher Coughlin and Mr. Abdeljalil Haib for their collaboration in this book project.

Agadir, Morocco Mohamed Nemiche
Rabat, Morocco Mohammad Essaaidi

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List of Editors and Contributors

Editors

Mohamed Nemiche is an Assistant Professor at Ibn Zohr University, Morocco. He received his Ph.D. from the University of Valencia, Spain, in 2002 and his Habilitation in Computer Science from Ibn Zohr University, Morocco, in 2012. His research interests are related to the study of complex systems with agent-based social simulation and mathematical modeling. Dr. Nemiche is the founder and the current president of the *Moroccan Society of Complex Systems* and the founder and cochair of the *World Conference on Complex Systems*. He is the winner of the *Kybernetes Research Award* (Pittsburg, USA) in 2002. Dr. Nemiche is the guest Editor of the special issue *Advances in Complex Intelligent Systems* in International Journal of Intelligent Systems and of the special issue *Conceptual Models of Complex Systems* in Systems Research and Behavioral Science.

Mohamed Essaaidi is an IEEE Senior Member and the current Director of National College of IT (ENSIAS) of Mohammed VI Souissi University, Rabat, Morocco. He was a Professor of Electrical and Computer Engineering at Abdelmalek Essaadi University, Morocco, from 1993 till 2011. He is the founder and Chairman of the IEEE Morocco Section, the founder of IEEE Computer and Communication Societies Joint Morocco Chapter, the founder and Chair of IEEE Antennas and Propagation Society and Microwave Theory and Techniques Society Morocco Joint Chapter, and the founder of IEEE Education Society Morocco Chapter. Prof. Essaaidi has authored and coauthored 5 books and more than 120 papers in international refereed journals and conferences in the field of Electrical, Information and Communication Technologies. He has been the Editor-in-Chief of *International Journal on Information and Communication Technologies*, Serial Publications, India, since 2007. Prof. Essaaidi also founded and has been the General Chair of the Mediterranean Microwave Symposium since the year 2000, Information and Communication Technologies International Symposium in 2005 and 2007, the International Conference on Multimedia Systems and Computing in 2009, 2011, and 2012, and the International Conference on Complex Systems in 2012. Prof. Essaaidi holds four patents on antennas for very high data rate UWB and multiband wireless communication systems and high resolution medical imaging systems.

Contributors

M. Bakhouya International University of Rabat, Sala el Jadida, Morocco

Omar Baz Ibn Zohr University, Agadir, Morocco

Pierre Bricage AFSCET The French Association for Systems and Cybernetic Sciences, Paris, France

IASCYS The International Academy for Systems and Cybernetic Sciences, Vienna, Austria

Helder Coelho BioISI and Faculdade de Ciências da Universidade de Lisboa, Lisbon, Portugal

Wei-Chien-Benny Chin Department of Geography, National Taiwan University, Taipei City, Taiwan

Vincenzo De Florio Vlaamse Instelling voor Technologisch Onderzoek, Remote Sensing Department, Boeretang, Mol, Belgium

Vrije Universiteit Brussel, Global Brain Institute & Evolution, Complexity and COgnition group, Pleinlaan, Brussels, Belgium

M. Essaaidi Ecole Nationale Supérieure d'Informatique et d'Analyse des Systèmes, Rabat, Morocco

Randy Gimblett School of Natural Resources and the Environment, The University of Arizona, Tucson, AZ, USA

Louis Klein The Systemic Excellence Group, Berlin, Germany

Pei-Chun Lai Department of Geography, National Taiwan University, Taipei City, Taiwan

F. Lachhab International University of Rabat, Sala el Jadida, Morocco

Ecole Nationale Supérieure d'Informatique et d'Analyse des Systèmes, Rabat, Morocco

Carlos M. Lemos CISDI and Instituto de Estudos Superiores Militares, Lisbon, Portugal

BioISI and Faculdade de Ciências da Universidade de Lisboa, Lisbon, Portugal

ISCTE-Instituto Universitário de Lisboa, Lisbon, Portugal

Rui J. Lopes ISCTE-Instituto Universitário de Lisboa, Lisbon, Portugal

Instituto de telecomunicações, Lisbon, Portugal

Humberto Mariotti Center for Workplace Diversity Research (CWDR), School of Advanced Studies, University of Phoenix, Phoenix, AZ, USA

Benoît Marx Université de Lorraine, CRAN, UMR 7039, Cedex, Vandoeuvre-les-Nancy, France

CNRS, CRAN, UMR 7039, Vandoeuvre-les-Nancy, France

Ahmed M'hamdi Ibn Zohr University, Agadir, Morocco

Javier Montero Faculty of Mathematics, Complutense University, Madrid, Spain

Gilles Mourot Université de Lorraine, CRAN, UMR 7039, Cedex, Vandoeuvre-les-Nancy, France

CNRS, CRAN, UMR 7039, Vandoeuvre-les-Nancy, France

Matjaz Mulej Faculty of Economics and Business, University of Maribor, Maribor, Slovenia

Nastja Mulej Nastja Mulej s.p., Ljubljana, Slovenia

Anca Maria Nagy-Kiss Environmental Research & Innovation Department, Luxembourg Institute of Science and Technology, Esch/Alzette, Luxembourg

Mohamed Nemiche Ibn Zohr University, Agadir, Morocco

R. Ouladsine International University of Rabat, Sala el Jadida, Morocco

Rafael Pla Lopez University of Valencia, Valencia, Spain

Aloah Pope School of Natural Resources and the Environment, The University of Arizona, Tucson, AZ, USA

José Ragot Université de Lorraine, CRAN, UMR 7039, Cedex, Vandoeuvre-les-Nancy, France

CNRS, CRAN, UMR 7039, Vandoeuvre-les-Nancy, France

Gracia Rodríguez-Caderot Faculty of Mathematics, Complutense University, Madrid, Spain

Pilar Romero Faculty of Mathematics, Complutense University, Madrid, Spain

Mark Rouleau Social Sciences Department, Environmental and Energy Policy Program, Michigan Technological University, Houghton, MI, USA

Georges Schutz Environmental Research & Innovation Department, Luxembourg Institute of Science and Technology, Esch/Alzette, Luxembourg

Fatima Ezzahra SFA Ibn Zohr University, Agadir, Morocco

Khabid Sidati Ibn Zohr University, Agadir, Morocco

Tzai-Hung Wen Department of Geography, National Taiwan University, Taipei City, Taiwan

Zdenka Ženko Faculty of Economics and Business, University of Maribor, Maribor, Slovenia

Part I
Societal and Ecological Systems

ProtestLab: A Computational Laboratory for Studying Street Protests

Carlos M. Lemos, Helder Coelho, and Rui J. Lopes

Abstract We present an Agent-Based model called ProtestLab for the simulation of street protests, with multiple types of agents (protesters, police and 'media') and scenario features (attraction points, obstacles and entrances/exits). In ProtestLab agents can have multiple "personalities" (implemented via agent subtypes), goals and possible states, including violent confrontation. The model includes quantitative measures of emergent crowd patterns, protest intensity, police effectiveness and potential 'news impact', which can be used to compare simulation outputs with estimates from videos of real protests for parametrization and validation. ProtestLab was applied to a scenario of policemen defending a government building from protesters (typical of anti-austerity protests in front of the Parliament in Lisbon, Portugal) and reproduced many features observed in real events, such as clustering of 'active' and 'violent' protesters, formation of moving confrontation lines, occasional fights and arrests, 'media' agents wiggling around 'hot spots' and policemen with defensive or offensive behaviour.

1 Introduction

Street protests and riots are manifestations of social conflict, which results from feelings of frustration due to relative deprivation (RD) and cleavages within the society (Gurr 1968). They may be large or small, peaceful of violent, organized or

C.M. Lemos (✉)
CISDI and Instituto de Estudos Superiores Militares, Lisbon, Portugal

BioISI and Faculdade de Ciências da Universidade de Lisboa, Lisbon, Portugal

ISCTE - Instituto Universitário de Lisboa, Lisbon, Portugal
e-mail: cmrso@iscte-iul.pt

H. Coelho
BioISI and Faculdade de Ciências da Universidade de Lisboa, Lisbon, Portugal

R.J. Lopes
ISCTE - Instituto Universitário de Lisboa, Lisbon, Portugal

Instituto de Telecomunicações, Lisbon, Portugal

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spontaneous, isolated or recurrent, and are an instrument by which citizens try to challenge authorities and influence the public opinion (Klandermans et al. 2014). History provides examples of large protests playing a decisive role in overthrowing regimes, as in the October Revolution in Russia in 1917 and the Iran Revolution of 1979 (Kuran 1989). Recently, widespread access to Social Networks (SN) and Information and Communication Technologies (ICT) allowed activists to convoke, coordinate and show protest events to a worldwide audience (Comninos 2011).

The relationship between protests and the political and social context can be viewed as a complex and path-dependent process. It involves multiple scales (ranging from social context to microscopic motivations and behaviours), factors (social, situational and individual), actors and interactions. Macroscopic context factors (political, social and economic) lead to conflict manifestations such as boycotts, strikes or protests, which in turn change the social context (e.g. the perceived grievance or the legitimacy of the government or central authority). These direct and feedback links may lead to stabilization or growth of the social unrest. Understanding, predicting and if possible controlling this process is an important topic in sociology, social psychology, political science, military and security studies, and more recently social simulation (Lemos et al. 2013).

Social conflict phenomena have been studied using Agent-Based models (ABM) (Gilbert and Troitzsch 2005; Lemos et al. 2013). Existing ABM of social conflict and violence are focused on specific scales and types of phenomena, and can be broadly classified as ‘abstract’, ‘middle-range’ and ‘facsimile’ (Gilbert 2007). ‘Abstract’ ABM have been proposed for explaining the dynamics and characteristic patterns of large-scale civil and ethnic violence (Epstein 2002; Epstein et al. 2001), revolution (Makowsky and Rubin 2011), worker protest (Goh et al. 2006), or even urban crime (Fonoberova et al. 2012), using a minimum number of agent types with very simple behaviour and interactions. ‘Middle range’ models are used to describe phenomena at definite space and time scales with context-specific information (Davies et al. 2013; Parunak et al. 2014). ‘Facsimile’ models attempt to describe the system’s dynamics with as much realism as possible, by considering the multiplicity of relevant actors, behaviours, interactions and scenario features. Models of this latter type have been proposed for studying crowd dynamics such as pedestrian flow in open or closed spaces (Pelechano et al. 2007; Still 2000), panic evacuation and crowd control (see TSO 2010a,b for a review), and for modelling riotous crowds which involve (possibly violent) interactions between protesters and police forces (Durupınar 2010; Lacko et al. 2013; Torrens and McDaniel 2013).

In this paper we describe a new ABM called ProtestLab of ‘facsimile’ type for modelling street protests, which is part of an ongoing work on social conflict simulation (Lemos et al. 2013). The purpose of ProtestLab is to simulate the emergent patterns in street protests, such as clustering of violent and active protesters, the formation of confrontation lines between violent protesters and police cordons, fights and arrests, and ‘media’ agents wiggling near fights, using a relatively simple reactive agent architecture common to all agent types. The research questions for the present work are:

- How do the features of the protest space and the crowd size, composition and initial placement affect the crowd formation patterns (wandering, clustering and fighting) and protest intensity?
- How does violent confrontation arise? Once initiated, does it spread to the bulk of the crowd or remains confined to specific types and clusters of protesters?
- How can different police actions influence the intensity of violent confrontation and the ability for defending a perimeter?

The novel features of ProtestLab with respect to other ABM are: (i) multiple types of agents ('protesters', 'cops' and 'media'), with multiple behaviours represented by agent subtypes; (ii) several types of scenario features (attraction points, obstacles, entrances and exits); (iii) a simple but efficient reactive agent architecture which allows all agents to have multiple goals and spatially oriented interactions; and (iv) quantitative measures of emergent crowd patterns, protest intensity, police vs protesters effectiveness and potential "media" coverage.

Three subtypes of 'protester' agents were considered, 'hardcore', 'hanger-on' and 'bystander', which broadly correspond to typical protester behaviours well characterized in micro-situational theories of violence (Collins 2008, 2009; Wikström and Treiber 2009), ABM of clustering and fighting (Jager et al. 2001), and also easily identified in many videos of real protests. Four subtypes of 'cop' agents were included, namely 'command', 'offensive', 'defensive' and 'multi role', which correspond to different mission profiles and assigned tasks in a police force. All agents can be one of four states, 'quiet', 'active' (waving, shouting, etc.), 'violent' (ripe for confrontation) or 'fighting'. Fights only occur when 'violent' protesters and cops are in contact, such as in body fighting (fights with weapons such as stones and tear gas are not considered in the present version of the model).

The advantage of ProtestLab with respect to existing ABM of crowd dynamics and violent confrontation is the capability of running realistic simulations of street protests with several hundred agents using small computers. The present version of ProtestLab is not intended for modelling fights between two groups (e.g. supporters of rival parties or football teams) mediated by a police force or events of collective violence that are not politically motivated, although the model can be extended to treat these cases. Consequently, the theories and models related to pedestrian flow, panic evacuation, ethnic violence or violence in two-party crowds (e.g. in football stadiums) will be mentioned only in the aspects relevant for the issues considered in ProtestLab.

The remainder of this paper is organized as follows. In Sect. 2 we present the theoretical background for ProtestLab. In Sect. 3 we describe the model entities, design concepts, quantitative measures of the emergent properties and issues related to parametrization and validation. In Sect. 4 we present the results of a set of simulations for a scenario of a police force defending the entrance of a government building from protesters, for different crowd densities and compositions (proportions of subtypes of 'protester' agents), average aggressiveness, and police 'personality' or mission profile and the action of a police "command" agent. Section 5 contains the discussion of the model results with emphasis on the model's capabilities, limitations and potential for a realistic description of the dynamics of street protests. Finally, Sect. 6 contains a summary of conclusions and a reference to intended further developments.

2 Theoretical Background and Previous Models

Several ABM have been proposed for the simulation of conflict phenomena of different types and scales. Epstein et al. (2001) introduced an 'abstract' ABM of large-scale rebellion against a central authority (Model I) or ethnic violence between two rival groups (Model II) with two types of agents, population and cops in a torus space environment. Population agents can be in three states ('quiet', 'active' or 'jailed'). Both types of agents have one movement rule M (move to a random empty cell within the agent's vision radius) and one action rule. Population agents that are not 'jailed' become 'active' according to the following threshold (action) rule:

$$G - N > T \tag{1}$$

where $G = H \cdot (1 - L)$, $G \sim \mathcal{U}(0, 1)$ is the (heterogeneous) grievance, $L \in [0, 1]$ is the (homogeneous) perceived legitimacy, $N = R \cdot P$ is the net risk perception, $R \sim \mathcal{U}(0, 1)$ is the (heterogeneous) risk aversion,

$$P = 1 - \exp(-k(C/A)_v) \tag{2}$$

is the estimated arrest probability, and T is a threshold. In Eq. (2), k is a constant with adopted value 2.3 (see Epstein et al. 2001 or Epstein 2002) and C_v and A_v are the numbers of 'cops' and 'active' citizens within the citizen's vision radius, respectively. Cops arrest a random 'active' agent within their vision radius (action rule) and arrested agents are removed from the model space for $J \sim \mathcal{U}(0, J_{max})$ cycles (jail term). This model successfully explained many important features of large scale civil violence or rebellion, such as intermittent bursts of violence (punctuated equilibrium), or the effects of gradual or sudden variations of the legitimacy and security apparatus (number of cops). The ABM of Epstein et al. (2001) has been extended by other authors and applied to other conflict phenomena such as worker protest (Kim and Hanneman 2011) or even urban crime (Fonoberova et al. 2012). However, 'abstract' ABM are unsuitable for modelling smaller scale phenomena like street protests, because they do not describe multiple actors, interactions and environmental (scenario) features.

Davies et al. (2013) presented a model of the London riots of 6th–10th August 2011, with rioters and policemen, which can be classified as 'middle-range'. This model considers definite space and time scales (streets and sites of London affected by the riots) and considers three processes: the decision to riot, the choice of the site for rioting and the interaction with the police forces. The decision to riot is modelled as a function of deprivation and the attractiveness of the sites for rioting. The choice of the rioting site is modelled via an utility function which takes into account the distance from the rioter's present position, the attractiveness and the level of deterrence expected at each site. As rioters interact with police they may be arrested with probability described by a function similar to that in Eq. (2). Although models of this type (e.g. Davies et al. 2013, Parunak et al. 2014) provide a representation of rioting events and include context-specific information for their parametrization and validation, they do not describe the micro-scale features of the interactions between protesters and the police forces (such as clustering of violent, active and quiet protesters, the formation of confrontation lines with fights and arrests, etc.).

Modelling micro-scale processes in crowd dynamics is a problem of great theoretical and practical importance. There are two types of crowd models relevant for the present work: models of pedestrian flow and crowd density, and models of riotous crowds. The study of pedestrian flow and the formation of spots with dangerous crowd density in panic evacuation has been intensely studied using methods from fluid dynamics (Helbing and Molnár 1995), cellular automata (Klüpfel 2003) and particle dynamics (Leggett 2004). Several well developed models are available for such applications (see Still 2000, and TSO 2010a,b for a review of existing models), which use a continuous space and time description of the motion of pedestrians as self-propelled particles subject to a force with three components (Social Force Model, Helbing and Molnár 1995) that express individual tendencies to (i) maintain a desired speed towards a wanted destination point; (ii) keep clear from other pedestrians or obstacles (repulsion force, decaying exponentially); and (iii) approach attractive features (such as other persons or displays) (Helbing and Molnár 1995; Helbing et al. 2001). The main difficulties are the need for algorithms for collision avoidance, description of the contact interactions between pedestrians and obstacles, and the need for integrating the equations of motion for each pedestrian (Pelechano et al. 2007). Discrete space and time models, in which pedestrians move in discrete steps and only occupy empty cells within their move range are simpler, because integration of the equations of motion for each pedestrian is not necessary (Klüpfel 2003). If the grid cell size is large enough for the repulsion forces to be negligible and only one agent per grid cell is allowed, then the agents' movement can be modelled in a very simple way. This latter approach was used in ProtestLab due to its simplicity and advantage for handling large numbers of agents.

Models for describing processes specific to riotous crowds, such as the formation of confrontation lines between protesters and police cordons, patterns of clustering, simple provocation or physical fights and arrests, are comparatively less developed than models of pedestrian flow and panic evacuation. Jager et al. (2001) presented an ABM of clustering and fighting between two parties (e.g. hooligans supporting two different football teams) with three kinds of agents, 'hardcore', 'hangers-on' and 'bystanders'. These subtypes are consistent with typical behaviours identified in micro-situational theories of violence (e.g. Collins 2008, 2009, Wikström and Treiber 2009) and can be confirmed in many videos of real protests. The agents' internal state is characterized by an 'aggression motivation' that increases/decreases depending on the difference between the number of visible agents of own and opposing groups. Agents approach members of own group with preference for their 'acquaintances' and, depending on their 'aggression motivation', may approach and start fighting with agents of the other group. The simulated results showed that fighting occurs when there are large asymmetric groups with significant proportions of 'hardcore', and that 'bystanders' are victimised. This model has the advantages of including aggression as a state variable, memory effects in the 'aggression motivation', and purposeful movement to simulate the collective behaviour of getting support before engaging in violence. However, it does not include connection between aggressiveness and social context variables and deterrence effects (there are no 'cop' agents).

Durupınar (2010) presented a sophisticated ABM for different types of crowds with psychological factors (personality, mood and emotions), based on a more sophisticated agent architecture which allows representation of emotion contagion. This model includes several types of agent personalities (protesters, agitators, and police agents) and events (such as fires and explosions), and has important features such as emotion contagion, multiple actors and multiple actions (waving, kicking and punching). Although the model is computationally demanding, Durupınar presents simulations with several hundreds of agents, including protesters marching in a street watched by policemen at the sides. However, it is not clear how the model would represent clustering, moving confrontation lines, fights and arrests in a realistic way over many time steps, and also lacks quantitative measures of these emergent features.

Torrens and McDaniel (2013) proposed an ABM for simulation of riotous crowds with four types of agents, 'Civil', 'Rebel', 'Jailed' and 'Police'[1] and the model space is a 2D torus in which sites can be blocked to represent obstacles. The attributes of the first three types of agents are the same as in Epstein's model (H, G, P_a, N and T) and the transition from 'Civil' to 'Rebel' is done using Eqs. (1)–(2). The geographic behaviour is implemented with three modules: spatial cognition, locomotion and steering. The spatial strategy (goal-driven approach/avoid movement) is implemented by defining weights for 'Rebel' and 'Police' agents to approach or avoid the other 'Police' and 'Rebel' agents. Although this model has sophisticated locomotion and steering modules and is able to represent both low and high density crowds, it falls short in other aspects critical for simulation of street protests. For instance, the set of agent types and their states is the same as in Epstein's 'abstract' ABM. Also, the approach/avoid weights are constant, whereas in reality they depend on local superiority or inferiority of protesters and police agents. The results reported in Torrens and McDaniel (2013) do not show the crowd patterns typical of street protests with violent confrontation, and for a simulation scenario of mass protest with 5000 citizens 42 % of the crowd ends up arrested, which is obviously unrealistic.

[1] In fact there are only two types of agents. 'Civil', 'Rebel' and 'Jailed' are different states of a single agent type, as in Epstein's ABM (Epstein 2002; Epstein et al. 2001).

Lacko et al. (2013) proposed an ABM for the simulation of urban riots, with police, protesters and a remotely operated vehicle (called "BOŽENA RIOT") designed for riot control, which considers cognitive modelling of agents, collision avoidance and crowd pressure calculations. The authors claim to have implemented the PECS (*P*hysical Conditions, *E*motional State, *C*ognitive Capabilities and *S*ocial Status) agent architecture (Schmidt 2002), and model fear in terms of the number of other persons within an agent's "intimate zone". Pressure calculations are performed by dividing the crowd in groups, then defining a group direction which is used to compute the pressure for individual agents in a virtual grid. However, these authors do not give details of their PECS implementation and do not report any results in Lacko et al. (2013). Thus, it is not possible to know whether or not the model reproduces realistic patterns of confrontation, how it handles variable density and pressure within the crowd, or how many agents can be included in one simulation.

In summary, existing ABM of riotous crowds have limited ability for modelling the variety of actors, states and micro-interactions in typical street protests. It would be desirable to integrate in one model different types of actors (protesters and policemen with differentiated behaviour), interactions (fights and arrests), scenario features, and quantitative measures of crowd patterns and protest intensity, for more realistic simulations. Thus, the purpose of ProtestLab is to overcome some of these drawbacks.

3 Model Description

In this section we present a summary description of the ProtestLab ABM, including the model entities and interactions, design concepts, process overview and scheduling, quantitative measures of crowd patterns and protest intensity, and parametrization and validation issues.

3.1 Agents, Scenario and Interactions

ProtestLab was implemented in NetLogo and has the following entities: `observer` (world, global variables), `turtles` (agents) and `patches` (space cells in the model space). Three types of agents were implemented, 'cops', 'protesters' and 'media'. The first two types correspond to the main interacting players and the latter is necessary for describing potential 'news impact' of protest events. The presence of "media" agents also changes the microscopic context by attracting curious protesters. Three subtypes of 'protesters' were considered, 'hardcore', 'hanger-on' and 'bystanders' which broadly correspond to characteristic behaviours observed in protests and reported in the literature (Collins 2008; Jager et al. 2001), and four subtypes of 'cop' agents, 'defensive', 'offensive', 'multi-role' and 'command', to reflect mission profile differentiation and allow a combination of command-oriented

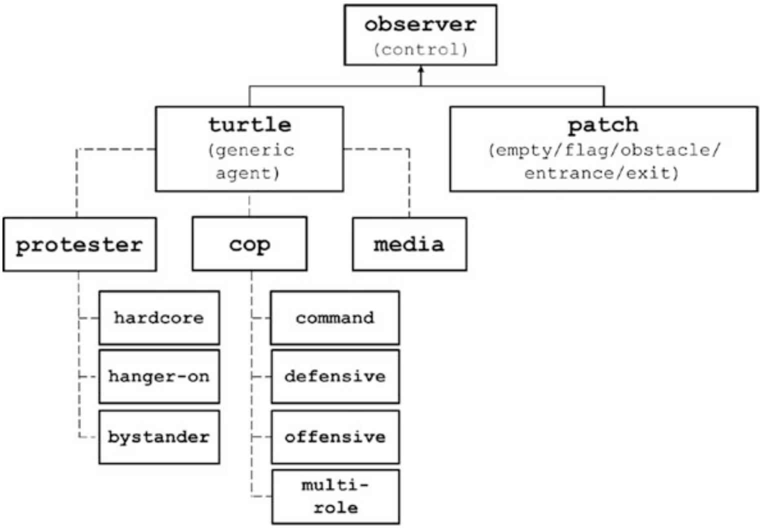

Fig. 1 Simplified class diagram for the agents and scenario features considered in ProtestLab

vs self-organized police behaviour. In the present version of ProtestLab, only one police commander agent is considered. Figure 1 shows the simplified class diagram for the model entities in ProtestLab.

In what follows A_i is a generic agent i and E_j a generic grid cell (patch) in the environment space. Cells E_j are described by their position and type, i.e. $S_{E_j} \in$ {`'empty'`,`'flag'`,`'obstacle'`,`'entrance'`,`'exit'`} and the scenario consists of a 2D grid (to represent a protest space with physical boundaries) of `max-pxcor` per `max-pycor` patches. It is assumed that the `patch` size has dimensions $1\,\text{m} \times 1\,\text{m}$ and the time scale (`tick` duration) is $1\,\text{s}$ which gives a constant speed of $1\,\text{m}\,\text{s}^{-1}$.[2]

3.2 Design Concepts and Agent Architecture

ProtestLab is based on the following design concepts: (i) agents are reactive and rule-based, move in discrete time and space increments (at most one agent per grid cell) and change their behavioural state and position depending on the local context; (ii) the agents' goal-directed movement is implemented by minimizing a penalty function that involves weights for avoiding or approaching other agents and scenario features (as in Ilachinsky 2004); and (iii) agents are activated in random order with a

[2]However, if the global variable `move-radius` is increased from its default value of 1 a velocity varying in steps of 1/`move-radius` can be introduced.

frequency that depends on their type (as explained in Sect. 3.3) and behavioural state and perform a `scan-plan-behave` sequence. Upon activation agents `scan` the environment to form their percept Pr_{A_i} (other agents and scenario features in sight), `plan` actions by updating their internal state, and `behave` by moving and doing an action that depends on their type and state, such as "taking pictures" of fights in the case of 'media' agents, or starting fights in the case of 'cops' or 'protester' agents.

The agent attributes common to all agents are their vision radius and angle (which define the vision cone for detecting nearby agents and scenario features) and move radius (distance an agent can travel in one time step measured in units of patch length), which are defined as input variables. The internal state I_{A_i} of A_i consists of the agent's behavioural state $S_{A_i} \in \{\texttt{quiet,active,violent,fighting}\}$, personality vector ω_{A_i} (described below), current position $\boldsymbol{x} = (x, y)$, intended (planned) position $\boldsymbol{x}^*$, and if $S_{A_i} = \texttt{fighting}$ the number of time steps to the end of fight, stored in one of two variables, `attacking` or `defending` (to differentiate fights initiated by 'cops' from those initiated by 'protesters'). 'Cops' also have a `waypoint` variable for storing an eventual patch that the 'command cop' ordered to defend. Figure 2 shows the agents' architecture used in ProtestLab and helps understanding the workings of the `scan-plan-behave` sequence of the agent cycle. In this figure $\mathbb{A}$ is the set of all agents, $\mathbb{E}$ is the set of environment features, S_{A_i} is the agent's behavioural state, $\boldsymbol{\omega}_{0,A_i}(I_{A_i}, Pr_{A_i})$ and $\boldsymbol{\omega}_{A_i}(I_{A_i}, Pr_{A_i})$ are the default and context-adjusted personality vectors of agent A_i respectively (as explained below), Ac is the agent's action and $f(\boldsymbol{x}, S_{A_i}, \boldsymbol{\omega}_{A_i}(I_{A_i}, Pr_{A_i}))$ is the agent's function (see e.g. Wooldridge 2009 for the terminology).

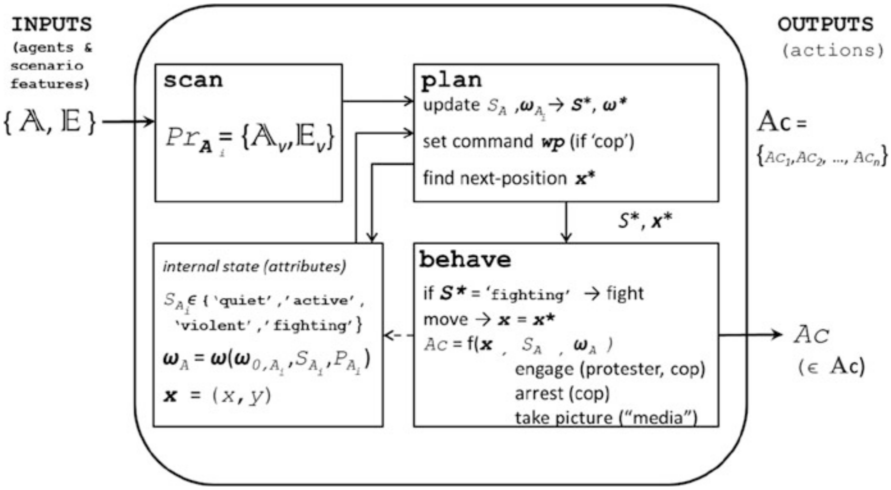

Fig. 2 Agent architecture diagram

3.2.1 Agents' Movement

Agents move to the centre of the empty patch $(\hat{x}, \hat{y})$ within their move range that minimizes the penalty function

$$V_{A_i}(x, y, I, Pr_{A_i}) = \frac{\boldsymbol{\omega}_{A_i}(I, Pr_{A_i})}{\|\boldsymbol{\omega}_{A_i}(I, Pr_{A_i})\|_1} \cdot (SD(x, y) - SD(x_0, y_0)) \tag{3}$$

where

$$SD(x, y) = \sum_{F_k \in Pr_{A_i}} \left(\sum_{j=1}^{N_{F_k}} D_{(x,y)} F_{k,j} \right) \tag{4}$$

is a double summation, in which the outer sum is taken over the feature sets F_k and the inner sum involves the distances from entity k (say one fighting 'cop') belonging to a feature set F_k (in this case the agent set of visible fighting 'cops') to point (x, y), and (x_0, y_0) is the current position of agent A_i.[3] Table 1 shows the components of the default personality vector $\boldsymbol{\omega}_{0,A_i}$ for all agent types and subtypes. Weights have absolute value between 5 (very high) and 0 (neutral, meaning that the agent is indifferent to entities of the corresponding feature). Positive weights result in attraction and negative weights in repulsion relative to the corresponding feature. The method of minimizing a penalty function allows the implementation of multi-goal driven movement with a single rule, without the complications of the "combinatorial explosion problem" that would arise with a rule-based **IF** `<context>` **THEN** `<action>` formulation (Ilachinsky 2004).

The penalty-minimizing method of inducing goal-driven movement weights perceived entities with context-dependent motivations or tendencies, but the formulation in Eqs. (3)–(4) is not suitable for targeted movement towards a particular position or agent. For example, a 'cop' A_i may have a motivation to go to a way-point (x_{wp_i}, y_{wp_i}) to defend that position, support other 'cops' or engage a protester. 'Cops' may also be ordered by a command agent to go to a specific way-point (x_{wp_c}, y_{wp_c}) (e.g. site to be protected or violent protester to be engaged). Denoting by $(\hat{x}_{wp}, \hat{y}_{wp})$ the position of the patch centre within the agent's move range nearest to the way-point, the next position will be $(\hat{x}, \hat{y})$

$$(\hat{x}, \hat{y}) = \frac{(\hat{x}_{V_{A_i}}, \hat{y}_{V_{A_i}}) + \alpha_i(\hat{x}_{wp_i}, \hat{y}_{wp_i}) + \alpha_c(\hat{x}_{wp_c}, \hat{y}_{wp_c})}{1 + \alpha_i + \alpha_c} \tag{5}$$

where α_i is the weight for moving towards an individually selected target and α_c is the command weight (or "obedience level") to go to (x_{wp_c}, y_{wp_c}). Depending on the

[3]The L_1 norm $\|\boldsymbol{x}\|_1 = \sum_{i=1}^{N} |x_i|$ in Eq. (3) was introduced as a normalization factor, so that personality vectors of different agents can be inspected and compared if required.

Table 1 Components of the default personality vector for all agent types and subtypes

	Fighting protester ω_0	Violent protester ω_1	Active protester ω_2	Quiet protester ω_3	Fighting cop ω_4	Violent cop ω_5	Active cop ω_6	Quiet cop ω_7	Fighting media ω_8	Quiet media ω_9	Flag ω_{10}	Obstacle ω_{11}	Entrance/exit ω_{12}
'Hardcore' protester	2	2	1	0	5	4	3	2	0	0	5	−1	0
'Hanger-on' protester	−2	−1	0	0	−2	−1	1	1	−2	3	1	−1	0
'Bystander' protester	−5	−3	−1	0	−5	−3	−1	0	−5	1	0	−1	1
'Command' cop	0	0	0	0	0	0	0	0	0	0	0	0	0
'Defensive' cop	0	0	0	0	5	5	5	5	0	0	5	5	0
'Offensive' cop	5	5	1	0	5	5	3	1	0	0	1	1	0
'Multi-role' cop	3	3	1	0	3	3	1	1	0	0	3	3	0
'Media'	3	1	0	−1	3	1	1	0	−1	1	1	−1	0

A positive sign means attraction and a negative sign means repulsion internal state I_{A_i} and percept P_{A_i} the components of the personality vector of agent A_i may change by the application of context rules that provide adaptation to the local context (as in Ilachinsky 2004). These context rules are different for each agent type and subtype.

Table 2 shows the names of the context rules and the components of the personality vector that change by their application for all agent types and subtypes in the model. The 'hardcore' cluster rule decreases attraction to flags when less then ten 'violent' or 'fighting' protesters are visible by setting $\omega_{10} = 1$; the 'pursue cops' rule increases attraction towards cops when protesters have a superiority of four to one, by setting $\omega_{5,6,7} = 5$; and the 'avoid cops' rule reverses the signs of ω_{4-7} when protesters are outnumbered in a proportion equal or greater then two to one. Notice that the conditions that activate the avoid/approach context rules are mutually exclusive. The context rules for all other agent types and subtypes follow the simple principles illustrated for the 'hardcore' context rules.

3.2.2 Agents' State Transitions

Transitions of behavioural state ('quiet' $\Leftrightarrow$ 'active' $\Leftrightarrow$ 'violent') are modelled differently for each type of agent. For 'protester' agents, these transitions are described using a variant of the Epstein et al. (2001) threshold rule (Eq. (1)) which, although introduced in the context of 'abstract' ABM, offers a simple alternative for modelling aggression and fear in politically-motivated protests, and is consistent with the micro-sociological theories of violence (Collins 2008, 2009): predisposition can be represented by the grievance and risk aversion terms, situational influence and deterrence by the form of the arrest probability function, and the "barrier" of tension-fear by the threshold. More specifically, behavioural state transitions of 'protester' agents are modelled using the following rules:

$$\text{if } G - (R \cdot P_a + T) > 0, \text{ turn 'active'} \tag{6}$$

$$\text{if } G - 2 \cdot (R \cdot P_v + T) > 0, \text{ turn 'violent'} \tag{7}$$

where $P_a = 1 - \exp(-k\lfloor C/A \rfloor_v)$, $P_v = 1 - \exp(-k\lfloor 2 \cdot C/(V + (1/2) \cdot A) \rfloor_v)$. In these equations G is the grievance, R is the risk aversion, T is the threshold, v is the number of visible 'violent' protesters, A is the number of visible 'active' protesters, C is the number of visible 'cops' and P_a and P_v are the estimated arrest probabilities for 'active' or 'violent' protesters respectively. The factor two in Eq. (7) and in the expression of P_v accounts for the increased risk and local superiority required for protesters to engage 'cops'. The factor $1/2$ that multiplies A in the denominator of the floor function accounts for the effect that one 'energizing active' is less influential than a 'violent' protester.

'Cops' change their behavioural state depending on 'approaching' protesters (defined as those at a distance smaller than 5 m), 'closing protesters' (defined as those at a distance smaller than 2.5 m), protesters at a distance from the nearest

Table 2 Context-rule names and personality vector components changed by them, for all agent types and subtypes in ProtestLab

	Rule name	Weights changed	Rule name	Weights changed	Rule name	Weights changed	Rule name	Weights changed
'Hardcore' protester	Cluster	ω_{10}	Pursue cops	ω_{5-7} ω_{10}	Avoid cops	ω_{4-7}		
'Hanger-on' protester	Keep-clear	ω_{0-7}	Cluster	ω_{2}	Turn 'hardcore'	ω_{0-12}		
'Bystander' protester	Keep-clear	ω_{0-7}	Turn 'hanger-on'	ω_{0-12}	Turn 'hardcore'	ω_{0-12}		
'Defensive' cop	On-station	ω_{0-12}	Engage trespassing	Variable				
'Offensive' cop	On-station	ω_{0-12}	Pursue protesters	ω_{2} $\omega_{6,7,10,11}$	Retreat	ω_{1} $\omega_{6,7,10,11}$	Support	ω_{0-12}
'Multi-role' cop	On-station	ω_{10-11}						
'Media'	Keep-distance	ω_{0-7}						

flagged cell smaller than 5 m, and protesters trespassing the defensive perimeter (on flagged cells). ‘Defensive’ cops turn ‘active’ if they see closing ‘quiet’, approaching ‘active’ or ‘violent’, or protesters approaching the defensive perimeter; and ‘violent’ if they see closing ‘violent’ or trespassing protesters. ‘Offensive’ cops turn ‘active’ if they see closing ‘quiet’ or approaching ‘active’ or ‘violent’ protesters; and ‘violent’ if they see closing ‘active’ or ‘violent’ protesters. ‘Multi-role’ cops turn ‘active’ if they see closing ‘quiet’, approaching ‘active’ or ‘violent’, or protesters approaching the defensive perimeter; and ‘violent’ if they see closing ‘active’ or ‘violent’, or trespassing protesters. In the present version of ProtestLab, the only cop ‘command’ agent does not change state. ‘Media’ agents are either ‘quiet’, or ‘fighting’ when engaged by ‘violent’ cops.

Fights were implemented in the `behave` step of agents’ activation using simple rules suggested from observations of videos. In the present version of ProtestLab (March 2016) fights have a fixed duration defined by the user (with default value 5 s). ‘Cops’ attack protesters within their move range that are ‘violent’ or trespassing the defensive perimeter, if they have at least two other supporting (backup) ‘cops’ within their move range. ‘Media’ agents do not turn ‘violent’ but they may be engaged by cops if they attempt to trespass the defensive perimeter. The `attacking` agent variable of the attacking ‘cops’ and the `defending` agent variable of the attacked protester is set equal to the fight duration. ‘Violent’ protesters may engage ‘cops’ in a similar way, but they must have at least four supporting ‘violent’ protesters within their move range. When agents are fighting, their `attacking` or `defending` variable is decremented. When there is only one time step to end the fight they plan to withdraw as far as possible from the opponent (overriding the penalty calculations described above). At the end of a fight an attacked protester is arrested (removed from the protest space) if the attacking cops have a local superiority of more than three to one within the protester’s move range, otherwise it breaks free. In a similar way, isolated ‘cops’ are “knocked out” and removed from the protest space if there is a local superiority of ‘violent’ protesters of more than four to one within the cop’s move range.

3.3 Process Overview and Scheduling

The model was implemented in two procedures, `setup` and `go`. Procedure `setup` clears all entities (agents and scenario features) and variables from the previous simulation and resets the cycle counter; builds the environment space (obstacles, flags, entrances and exits); builds the agents list and introduces agents in the simulation space; initializes the counters for the number of fights, arrests, ‘cops’ knocked down and “pictures” taken by ‘media’ agents; displays the agents; and opens the output file for writing the time history of the simulation. Procedure `go` tests for termination; activates all agents by random order; calls the `scan`, `plan` and `behave` procedures in succession for each agent; updates the counters of the number of fights, arrests, ‘cops’ knocked down and ‘pictures’ taken by ‘media’ agents since the beginning of the simulation; updates the quantitative measures of the emergent crowd patterns (see Sect. 3.4); and updates the display. All agents are activated in random order with an average frequency that depends or their type and state. For 'violent' and 'fighting' protesters, non-fighting 'cops', and 'media' agents, that frequency is 1/`fight-duration`; for 'active' and 'quiet' protesters it is 1/(2∗`fight-duration`) and 1/(8∗`fight-duration`) respectively. 'Violent' and 'fighting' cops are activated with average frequency 1 (i.e. once per time cycle). This reflects the influence of the behavioural state in arousal and decision speed, as done in the ABM of Jager et al. (2001).

3.4 Quantitative Measures of Emergent Properties

In this section we describe the quantitative measures of crowd patterns, protest intensity and police vs protesters performance, and their integration in NetLogo's Interface Tab. We considered four types of emergent properties: (i) crowd patterns (clustering); (ii) police vs protesters interaction; (iii) protest intensity and collective behaviour; and (iv) potential "news" impact. For each class we selected the representative properties shown in Table 3 and implemented their computation at each time step.

Clusters are identified using a recursive depth-first search on the Moore neighbourhood of a randomly chosen starting agent in the selected agent set (e.g. all 'protester' agents with behavioural state 'violent'). This algorithm is essentially the same used to find connected components in a network. The clusters' spatial orientation is determined by computing the principal axes of inertia from the agents' coordinates (assuming for simplification that all agents have equal mass).

3.5 Parametrization and Validation

We analysed a large number of videos from two sources, YouTube for protests in different countries, and authors' own records for protests in Lisbon, Portugal. 30 videos from ten countries were selected which showed one or more of the following features: (i) global views of the crowd and clusters (of violent, active and passive protesters) within the crowd; (ii) confrontation lines between police and protesters; (iii) frequency, duration and local superiority of protesters and police in fights, arrests and 'media' actions; and (iv) specific police and protester tactics.

Table 3 Quantitative measures of emergent properties built in ProtestLab

Emergent properties	Quantitative measures	Implementation
Crowd patterns	Cluster size histogram, 'violent' and 'fighting' protesters	Cluster detection procedures
	Cluster size histogram, 'active' protesters	Cluster detection procedures
	Cluster orientation of largest cluster of 'violent' and 'fighting' protesters	Procedures for finding principal axes of inertia
Police vs Protesters	Number of 'violent' and 'fighting' protesters on defensive perimeter	NetLogo primitives
	Number of 'active' protesters on defensive perimeter	NetLogo primitives
	% defensive perimeter (territory) covered by police	NetLogo primitives
	% defensive perimeter (territory) occupied by protesters	NetLogo primitives
Protest intensity (collective behaviour and mimetic effects)	Number of 'fighting' protesters	NetLogo primitives
	Number of 'violent' protesters	NetLogo primitives
	Number of 'active' protesters	NetLogo primitives
	Number of 'quiet' protesters	NetLogo primitives
Potential 'news' impact	Number of 'pictures' of fighting episodes taken by 'media' agents	List-processing NetLogo primitives

For each video we obtained visual estimates[4] of:

- Crowd density, average activity and aggressiveness, proportions of 'violent', 'active' and 'quiet' protesters;
- Spatial clustering patterns 'violent', 'active' and 'quiet' protesters;
- Distances between police cordons and protesters;
- Distance at which 'media' agents typically move, wiggling around 'hot spots';
- Fight duration and number of attacking and defending agents involved in fights (policemen or protesters);
- Number of policemen required to arrest one protester, or number of protesters needed to beat and isolated police agent;

[4]Quantitative analyses of videos accessible from YouTube are limited due short duration, unsteady camera handling and poor still-image quality. Videos that show localized fights usually do not show global views of the crowd and vice-versa. Also, it is difficult to identify protesters that are active or passive to estimate their proportions. In our analyses of videos we expect errors of 1–2 m on distances and 20 % on proportions, which we consider acceptable for purposes of the present work.

Table 4 Analysis of selected videos: visual estimates, related model parameters and context rules, and adopted value/range for the parameters considered

Item	Visual estimate	Related model parameter(s)	Related context-rule(s)	Adopted value/range
Number of 'violent' protesters	10–25	Number of 'hardcore', average hardship (H)	Cluster	10–20
% of 'active' protesters	20–80 %	Number of 'hanger-on', average hardship (H)	Cluster turn-hardcore	30–70 %
% of 'quiet' protesters	10–90 %	Number of 'bystander', average hardship (H)	Keep-clear cluster turn-hardcore	70–30 %
Distance cop-violent	1–2 or 5–10 m	ω_1 and ω_{4-7}	Pursue/avoid engage trespassing	see Table 1
Distance cop-active	5–15 m	ω_2 and ω_{4-7}	Engage trespassing	see Table 1
Distance cop-quiet	>15 m	ω_3 and ω_{4-7}	Engage trespassing	see Table 1
Distance media-fights	1–2 or 2.5–5 m		Keep-distance	see Table 1
Fight duration	5 s	`fight-duration`		5
Number of cops for one arrest	3–4	Fight end conditions		4
Number of protesters to neutralize one cop	5	Fight end conditions		5

The videos also convey a general picture of the social context, grievance motifs of the protesters and crowd aggressiveness. For instance, anti-austerity protests in European countries are markedly different from protests in Cairo or Istanbul with respect to both crowd and police tactics and aggressiveness. Table 4 shows the summary of the analysis of the visual estimates of the observed items. This analysis allowed a spiral-like process of tuning the values and/or ranges of the personality vector weights (see Tables 2 and 4) and the variables that control the activation of context rules. Despite the limitations of the process, the analysis of the videos improved the setting of the approach/avoid weights of the components of the agents' "default personality" vector, as well as setting the conditions for activation of the context and state-changing rules.

4 Results

We used ProtestLab to simulate a scenario of a police force defending the entrance of a government building, typical of protests near the Portuguese Parliament (Rua de São Bento, Lisbon, Portugal) which is well known to the authors. The protest space was defined as a 150 m × 60 m grid (closed boundaries). The access to an existing space in front of the building is a staircase about 25 m wide and 25 m long, where the police forces usually stand. The limits of the staircase and the walls facing the street on each side of it were defined by two sets of obstacle cells, each with a width of 48 m. The defensive perimeter was defined by flagging the cells on the bottom 10 m of the staircase (adjacent to the street).[5] The protest area was defined as a strip 30 m wide in front of the staircase and obstacles, with an entrance on the right and an exit on the left. In all simulations, 'cops' were initially placed on the defensive perimeter, 'media' agents to the right of the staircase (the usual place were formal media teams stand, from where they can observe the confrontation zone at close range and be relatively safe in case of a sudden, unanticipated police charge), and protesters in random positions at a clear distance from the police force, with a few 'hardcore' in front of the crowd. The vision radius was set to 10 m, the vision angle to 190° and the move radius to 1 m for all agents. Protesters had their `hardship` (H) and `risk-aversion` (R) set to $H = 1$ and $R \sim \mathcal{U}(0, 1/2)$ for 'hardcore', and $H \sim \mathcal{U}(0, 1)$ and $R \sim \mathcal{U}(0, 1)$ for 'hanger-on' and 'bystander', so that 'hardcore' protesters have maximum grievance and reduced risk aversion relative to the other protesters.

Table 5 shows the initialization parameters for the initial number of agents of each type and subtype, `government-legitimacy` and `population-threshold` for all simulations presented and discussed below. Four different scenarios were simulated of a crowd of 1300 protesters confronting a police force of 50 agents. Twenty simulations were performed for each scenario, each with a duration of 3600 time cycles (corresponding to 1 h). The simulated crowds consisted of 15 'hardcore', 300 'hanger-on' and 685 'bystander' protesters, which are realistic proportions in this type of event. The AR1 scenario is a reference simulation setting with the crowd confronting 'multi-role' cops (the first 'cop' subtype developed Lemos et al. 2014). In simulation AR2, 'multi-role' cops were replaced by 'defensive' cops, to investigate how the performance of the latter improves the realism of the simulations. Simulation AR3 was performed to illustrate the effect of introducing a 'command agent'. In simulations AR1-AR3, the legitimacy was set to 0.75, to represent a situation of a democratic government facing strong discontent (e.g. due to austerity measures). Simulation AR4 was planned to show how the proportion of 'violent' protesters increases as the government legitimacy is reduced (increasing the mean grievance of 'hanger-on' and 'bystander' protesters),

[5]We only represented the 10 m strip of the staircase adjacent to the street to reduce the number of cells and make the figures more legible. This is not a strong limitation since the important dynamics usually unfolds on the part of the staircase included in the model.

Table 5 Table of initial number of agents, government legitimacy and population threshold used in the simulations of the "protect Parliament" scenario

Simulation scenario	Number of cops	Number of protesters	Number of 'media' agents	Government legitimacy (L)	Population threshold (T)
AR1	50 'multi-role'	15 'hardcore'	2	0.75	0.10
		500 'hanger-on'			
		800 'bystander'			
AR2	50 'defensive'	15 'hardcore'	2	0.75	0.10
		500 'hanger-on'			
		800 'bystander'			
AR3	1 'command'	15 'hardcore'	2	0.75	0.10
	50 'defensive'	500 'hanger-on'			
		800 'bystander'			
AR4	1 'command'	15 'hardcore'	2	0.50	0.10
	50 'defensive'	500 'hanger-on'			
		800 'bystander'			

and how the crowd patterns change accordingly. Three representative results will be presented. The first shows how ProtestLab handles the evolution of crowd patterns and confrontation in a protest, for one simulation of the AR3 scenario. The second shows the differences in the simulated crowd patterns and protest intensity between the AR3 and the other scenarios. The third shows the use of the quantitative measures of emergent properties for interpreting simulation results.

Figure 3 shows four perspective (3D) snapshots of the protest space for one simulation of the AR3 case. A police commander agent was introduced, which gave an order to all 'cops' to occupy the front rows of the staircase and stay there, with $\alpha_c = 20$ in Eq. (5). 'Cops' formed a cordon that held tight, to keep protesters from trespassing. At $t = 60$ s (Fig. 3a), the simulated protest "heated up" with a few protesters turning 'violent' and advancing forward from the bulk of the crowd to form a small cluster, and other protesters becoming 'active'. At $t = 600$ s (Fig. 3b), a cluster of 'violent' protesters assembled in front of the police cordon, coming from the sides and from the bulk of the crowd in front of the staircase. The police cordon remained in line formation, as ordered by the 'command' cop, without chasing or dispersing protesters (as would occur with 'multi-role' and 'offensive' cops). Clusters of 'active' protesters were forming in the crowd and a group or 'energizing active' joined the 'violent' cluster provoking the police. At $t = 712$ s (Fig. 3c), a fight began between the 'violent' protesters and police, and the two 'media' agents converged towards the "hot spot". At $t = 1800$ s, several protesters were fighting, and an arching pattern of 'active' protesters began to form behind the confronting cluster of 'violent' protesters. 'Cops' behind the first line moved from left to right to support comrades at "hot spots". Occasionally some 'cops' on the first line left their positions but the gaps were filled by other 'cops' to keeping the cordon unbroken. The cluster of 'violent' and 'active' protesters continued to confront the police cordon at a distance between 5 and 10 m, with small groups

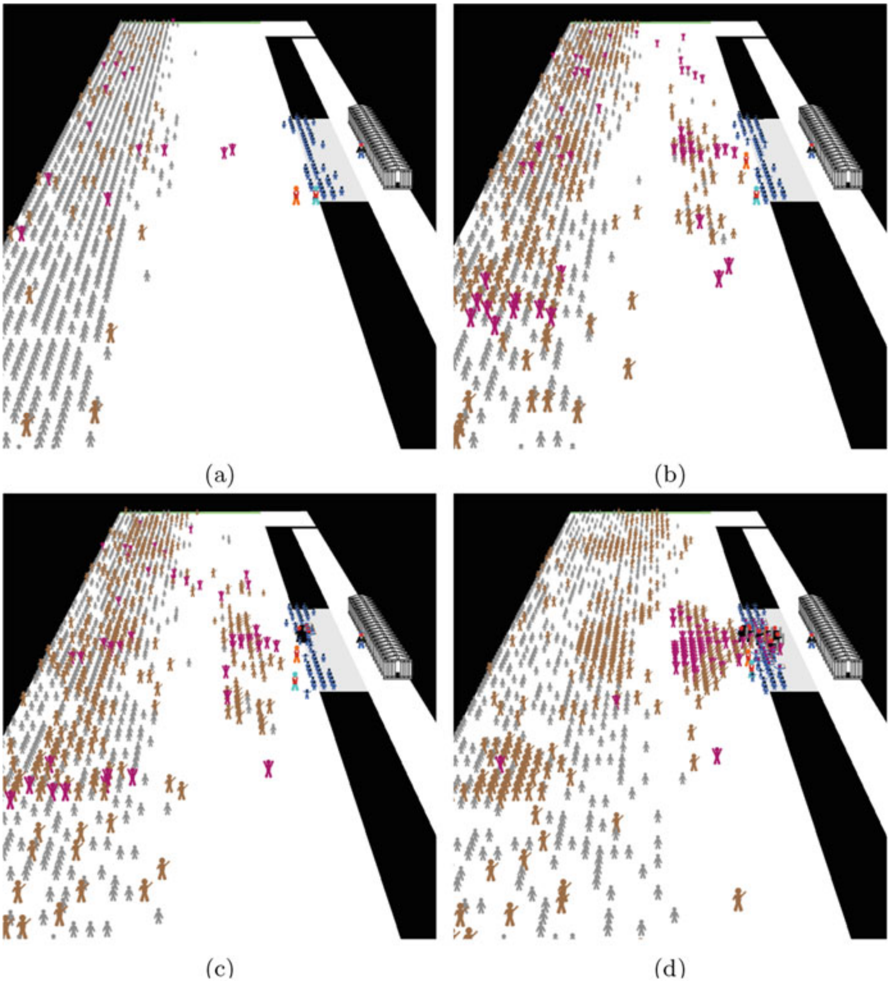

Fig. 3 Snapshots of the protest space for a simulation of the AR3 scenario at times 60 s (**a**), 600 s (**b**), 712 s (**c**) and 1800 s (**d**). In these figures, 'quiet', 'active' and 'violent' protesters are represented by *grey*, *brown* and *red* human figures, respectively; 'quiet', 'active' and 'violent' cops by *blue* figures, *blue* figures with raising arms and (larger) *blue* figures raising a little baton, respectively; the 'command' cop is represented by a little police figure, in front of the building; fighting' protesters and cops are represented by *black* figures; and 'media' agents by little human figures with a jacket

of 'violent' protesters advancing to engage 'cops' and then retreating. This cluster pushed the police cordon slowly, with 'cops' fighting fiercely. This suggests that when cops are too rigid they may withstand heavy 'pounding' due to successive attacks, so that a police charge (with 'offensive' cops) may be ordered to disperse violent protesters, as shown in Lemos et al. (2015).

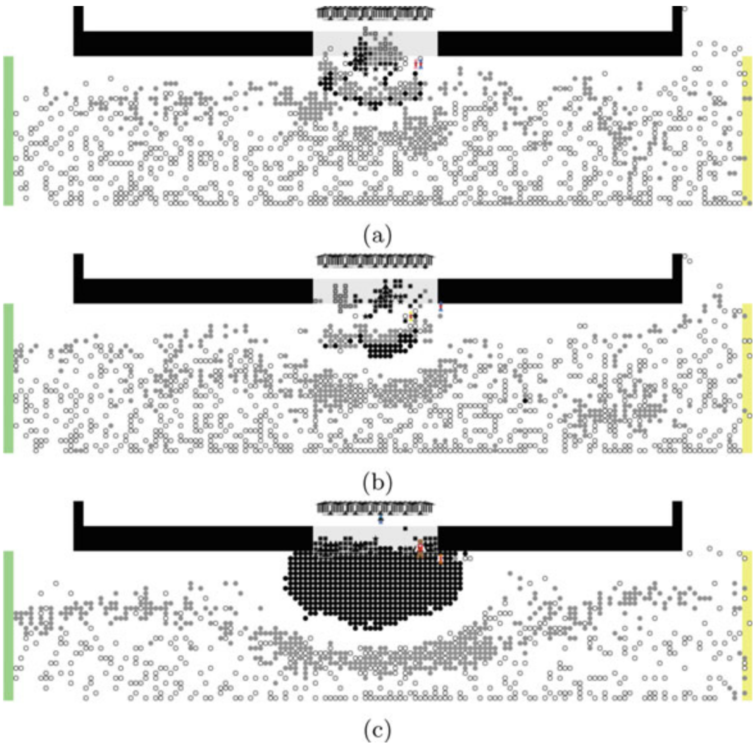

Fig. 4 Snapshots of the protest space for simulations of the AR1 case at $t = 2438$ s (**a**), AR2 case at $t = 2262$ s (**b**) and AR4 case at $t = 2015$ s (**c**). Non-fighting 'protesters' and 'cops' are represented by *circles* and *squares*, respectively. The *circles* and *squares* are hollow for 'quiet', *grey* for 'active' and *black* for 'violent' agents. Fighting 'protesters' are represented by *black stars* and fighting 'cops' by *black triangles*. 'Media' agents are represented as little persons with jackets, and double size when caught in a fight (i.e. engaged by the 'cops'). If present, the police commander is represented by a little 'cop' figure

After considering the evolution of a simulated protest for the AR3 case, the differences between the AR3 case and the other scenarios will be illustrated, in terms of the resulting crowd patterns, police vs protesters domination of the "disputed territory" and intensity of the confrontation. Figure 4 shows three interesting snapshots of the protest space, obtained in simulations of the AR1, AR2 and AR4 scenarios. In the snapshot of the AR1 simulation (Fig. 4a), the staircase is defended by 'multi-role' cops acting in autonomous mode (no command orders). The simulated patterns of crowd clustering and confrontation were similar to those of the AR3 case presented above, but with more pronounced arch shape. 'Violent' and 'energizing active' protesters formed one arch-like cluster at about 5 m distance from the police formation, and 5–10 m behind them there was a larger and wider arch-like pattern with clusters of 'active' protesters. 'Quiet' bystanders were dispersed over the protest space, standing still or wandering slowly at a safe distance from the confrontation area. The simulated behaviour of the police formation was not as realistic as that of the protesters: they concentrated at the centre of the staircase, leaving wide gaps on both sides from where protesters could infiltrate and invade the “disputed territory”. Figure 4b shows a snapshot of a simulation of the AR” case, where ‘multi-role’ cops were replaced by ‘defensive’ cops. In this case, ‘cops’ provided a better coverage of the area they had to defend. Because their formation was more efficient they repelled the protesters more effectively, resulting in more pronounced arching patterns than for the AR1 case. In the absence of a command agent, the ‘cops’ did not form a cordon (as in the AR3 case). The snapshot of the AR4 simulation shows the result of increasing the average grievance of the crowd due to lower government legitimacy ($L = 0.50$), with the staircase protected by ‘defensive’ cops and a ‘command’ agent. In comparison with the other cases, many more protesters turned ‘violent’. They formed a huge, very compact and aggressive mob, with very pronounced semi-circle shape, which pressed and slowly pushed the police cordon back into the staircase. The mob invested towards the police cordon so quickly that the two ‘media’ agents were caught, dragged and trapped in the middle of the ‘violent’ mass (one of them trespassed the staircase and was engaged by the police). This situation can be observed in videos of violent protests in Egypt during the “Arab Spring”, in contrast with e.g. anti-austerity protests in European countries where confrontation is driven by a few agitators.

Figure 5 illustrates the model interface at the end of one simulation of the AR4 scenario, showing the protest space, and various plots and monitors of quantitative measures of crowd patterns (cluster size and orientation), protest intensity (numbers of ‘active’, ‘violent’ and ‘fighting’ protesters, as well as the cumulative numbers of fights, arrests and “cops knocked down”), police vs protesters (number and % of the staircase area occupied by protesters) and potential “news impact” (cumulative

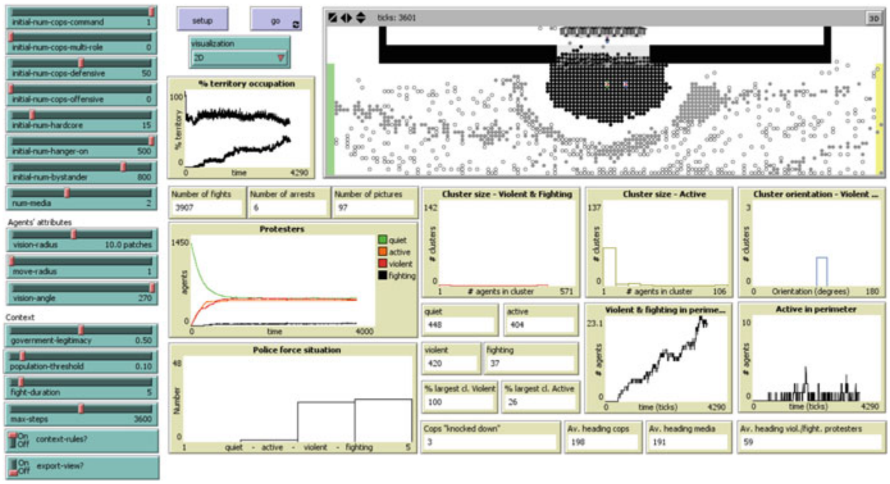

Fig. 5 ProtestLab’s NetLogo interface at the end of one simulation of the AR4 case

number of “pictures” taken by ‘media’ agents). The simulated protest “heated-up” so that at about 20 min after the start the proportions of ‘quiet’, ‘active’, ‘violent’ became almost equal (the final number of protesters in each state is shown in monitors), with small fluctuations. The cluster size histogram shows that almost all ‘violent’ protesters were concentrated in one large cluster, with orientation close to 90° (the geometric orientation of the staircase and police cordon). The plots of “territory occupation” and number of ‘protesters’ trespassing the defensive perimeter shows that the mass of ‘violent’ protesters pushed the whole police cordon steadily, gaining territory. At the end of the simulation almost all ‘cops’ were ‘violent’ or ‘fighting’. Six ‘protesters’ were arrested, three ‘cops’ were “knocked down” and ‘media’ agents took 97 “pictures”.

The quantitative measures of emergent properties implemented in ProtestLab provide a rich and coherent “narratives” of the simulated protests, but can also be used to compare different scenarios via post-processing. Figure 6 shows the time evolution of the median of the number of fights, arrests, “pictures” taken by ‘media’ and “cops knocked down” for all scenarios simulated. Fights began earlier (about 5 min after the start of the simulation) and reached a much higher number in case AR4 than in the other three cases, showing that the average crowd grievance was

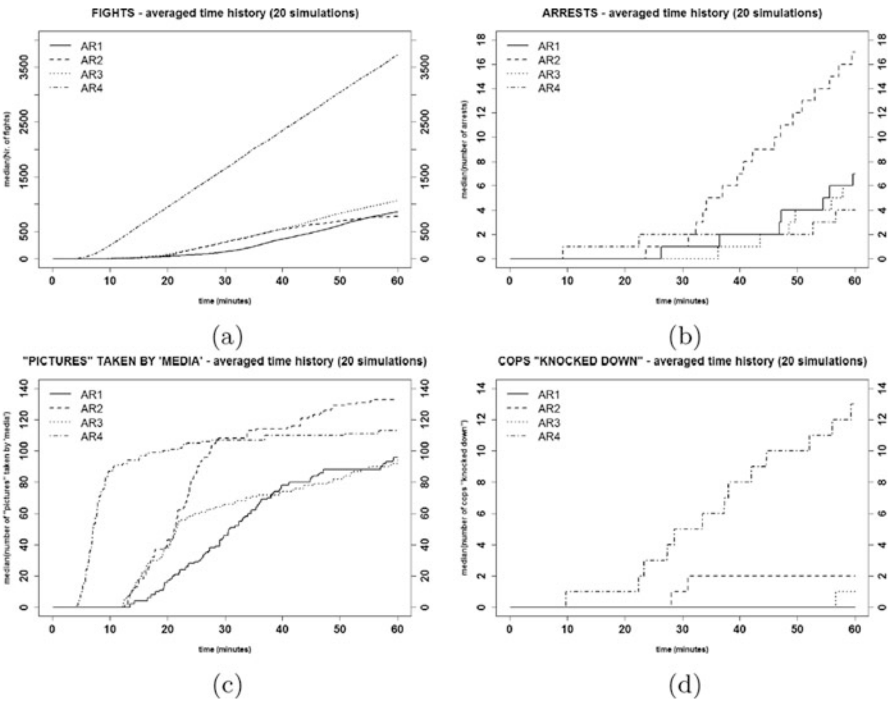

Fig. 6 Time evolution of the median of the cumulative number of fights (**a**), arrests (**b**), “pictures” taken by ‘media’ (**c**) and “cops knocked down” (**d**), for twenty simulations of the AR1, AR2, AR3 and AR4 scenarios

the chief factor of violent confrontation. Also, the number of 'cops' knocked down was more than six times larger for this case than for the other three. 'Defensive' cops without 'command' (case AR2) led to the largest number of arrests of the four scenarios. The number of "pictures" taken by 'media' shows that these agents began "taking pictures" by the same time fighting began but the number of records did not increase linearly (as did the number of fights) because 'media' agents avoided taking multiple "pictures" of the same fighters. In the AR4 scenario, they initially recorded many fights but then became stuck within the 'violent' mob. This prevented them from approaching the confrontation line were subsequent fights took place.

5 Discussion

The results show that ProtestLab is capable of reproducing in a realistic way many crowd patterns and micro-situational features observed in real events of the "protect Parliament" scenario. For instance, the formation of the elongated arching patterns, with the small phalanx of 'violent' protesters moving back and forth at $\sim$5–10 m in front of the police formation, the clustered arch of "active energizers" behind at $\sim$20 m (with a "clearance gap" from the confrontation) and 'bystanders' standing still at safe distance, or slowly wandering and occasionally leaving the protest space, is consistent with what is observed in video records of this type of event. Violence and activity did not propagate to the bulk of the crowd but remained confined to specific groups of protesters. These emergent spatial and behavioural patterns are also fully consistent with the micro-situational theory of violence (Collins 2008).

The programming of 'defensive' cops (default 'personality' and context-rules) was successful, in the sense that they provided a good perimeter coverage and prevented 'protesters' from breaching the perimeter, only fought when 'protesters' attempted to trespass or engage them, and arrested 'protesters' when they had enough numerical superiority to do so. The introduction of a 'command' agent lead to the formation of a tighter and more rigid police cordon. 'Media' agents wiggled around fights, "taking pictures" in-between the police cordon and the phalanx of 'violent' protesters, as is found in real events.

In all simulations, the number of arrests was small, even after an hour of activity, despite the relatively large crowd size and number of fights registered. This is a significant improvement over existing models of riotous crows (e.g. Torrens and McDaniel 2013), and provided realistic estimates of this measure of "protest intensity". In some simulations, one or two 'cops' were knocked down by protesters, which is also a realistic outcome which existing ABM of riotous crowds are unable to represent.

6 Conclusions and Future Developments

In this work an ABM called ProtestLab for simulation of politically-motivated street protests and violent confrontation was described. The model's capabilities were illustrated by its application to a typical scenario of a police force defending the entrance of a building from a crowd of protesters. In ProtestLab, all agents are reactive and based on a relatively simple architecture, with a modular `scan-plan-behave` cycle, one move rule that allows multi-goal purposeful movement, and one action rule. This allowed the development of a multiplicity of agents ('protesters', 'cops' and 'media'), with differentiated behaviours (via agent subtypes), and multiple possible behavioural states ('quiet', 'active', 'violent' and 'fighting'). The model also includes quantitative measures of crowd patterns (cluster size and orientation), coverage/occupation of the police's defensive perimeter, protest intensity, and potential "news impact".

The simulations showed the ability of ProtestLab for modelling a crowd of 1300 protesters with different aggressiveness confronting a police force of 50 'cops' for 1 h of simulated time, using a small computer. The model reproduced many emergent properties in this type of crowd event, such as the formation of a confrontation line between the police cordon and a loose phalanx of 'violent' protesters, moving back and forth with fights, occasional arrests or even 'cops' knocked occurring sporadically. ProtestLab also reproduced the arching pattern of 'active energizers' behind the 'few violent', aggregated in clusters, and the mass of 'bystander' protesters standing still or moving slowly, at a safe distance from the confrontation zone. Simulated 'media' agents wiggled around the fights to record episodes of violence, as is often observed in videos of real protests. ProtestLab also allowed the simulation of crowds with a few agitators where violence does not propagate to the bulk of the crowd (like those found in anti-austerity protests in Europe) or angry mobs in which a mass of protesters violently engage the police force (like those found in Egypt during the "Arab Spring"). The number of arrests or 'cops' knocked down was small, despite the large number of episodic fights and duration of the simulated events. The capability for modelling of this wide range of complex characteristics and emergent patterns of street protests in relatively large crowds, and their time over periods of about 1 h, represents a significant improvement over previous models of riotous crowds.

Due to the design concepts employed, ProtestLab is a flexible model and can be improved in many ways. Since the grievance G is related to "anger" (driving term) and the net risk N to "fear", one possible extension is reformulation of the transition rules in term of variables not related to political factors and conflict with a central authority. It is also possible to introduce a 'group tag' attribute to model confrontation between two rival groups mediated by a police force (e.g. supporters of rival parties or football teams).

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A Generic Agent-Based Model of Historical Social Behaviors Change

Ahmed M'hamdi, Mohamed Nemiche, Rafael Pla Lopez, Fatima Ezzahra SFA, Khabid Sidati, and Omar Baz

Abstract The primary theme of this chapter is trying to describe, discuss and understand how human societies change over time using agent-based modeling. Agents become a major paradigm of social simulation allow us to model the complex social phenomena under the bottom-up approach. Certainly one of the key points of the bottom-up approach is the emergence of macro level phenomena from micro level actions and interactions. The main objective of this work is to build a Virtual Social Laboratory, from Rafael Pla Lopez Social evolution model, in order to explore the social evolution of a set of artificial societies/agents that evolve within a grid of cells which are characterized by a level of natural resources (artificial environment). This laboratory can help to explore and understand the East–West duality, the North–South Divide, the Human migration process, the globalization-polarization and some possible human social evolution.

1 Introduction

The primary theme of this chapter is trying to describe, discuss and understand how human societies change over time using agent-based modeling. Agents become a major paradigm of social simulation allow us to model the complex social phenomena under the bottom-up approach. Certainly one of the key points of the bottom-up approach is the emergence of macro level phenomena from micro level actions and interactions. The main objective of this work is to build a Virtual Social Laboratory, from Rafael Pla Lopez Social evolution model, in order to explore the social evolution of a set of artificial societies/agents that evolve within a grid of cells which are characterized by a level of natural resources (artificial environment).

A. M'hamdi • M. Nemiche (✉) • F. Ezzahra SFA • K. Sidati • O. Baz
Ibn Zohr University, Agadir, Morocco
e-mail: m.nemiche@uiz.ac.ma; nemiche@u.es

R. Pla Lopez
University of Valencia, Valencia, Spain
e-mail: Rafael.Pla@uv.es

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This laboratory can help to explore and understand the East–West duality, the North–South Divide, the Human migration process, the globalization-polarization and some possible human social evolution.

Understanding the historical human social change is a hard task. Social change refers to an alteration of social structures, including consequences in cultural symbols, norms, social organization, and values. The social change can evolve from a number of different sources, including social conflict (Karl Max, Dahrendrof (Dahrendorf 1958; Giner s.f.; Marx and Fredrick Engels 1888)), conflict between the norms of group behaviors (Rafael Pla-Lopez), social learning (diffusion), changes in the ecosystem, technological progress (as agricultural and industrial revolutions) and population growth.

2 Conflict as an Engine for Social Change

Conflict is a natural phenomenon in any human society; it is a social reality consubstantial with social life. The social conflict is not unusual, in fact the conflict is neither good nor bad it is an engine for social change (Giner s.f.). Conflict arises when resources, status and power are unevenly distributed among groups of same society (micro-conflict) or between different societies (macro-conflict).

Karl Marx has conceived society as an integrated organization shared among different social classes that are in permanent conflicting interests. The history of all hitherto existing society is the history of class struggles: Freeman and slave; feudal lord and peasant; bourgeois and proletarians (Marx and Fredrick Engels 1888). In a footnote added to the 1888 edition of the Communist Manifesto, Engels notes that of course the sentence "The history of all hitherto existing society" is only referring to written history, and that by then it was well known that there were no social classes in pre-history (Marx and Fredrick Engels 1888). According to Karl Marx social conflict is the conflict between social classes.

Ralf Dahrendrof agreed that class struggles were the basis of social conflicts in eighteenth and nineteenth centuries societies. In the twentieth century the category of social class was too broad to be useful in social analysis. A significant number of conflicts have been presented in the same class; so that could not be explained by traditional Marx's conflict theory as a class against another. According to Dahrendorf, this is the unequal distribution of authority that is the basis of social conflicts in society. Each class has an opposite position vis-à-vis the authority, the ruling class will try to maintain its position, while the dominated class will act to change this situation. Social conflict is a struggle to maintain or change the distribution of authority and not a struggle for the possession of means of production in capitalist societies as claimed by Karl Marx (Dahrendorf 1958). For Dahrendorf conflict is manifested as a struggle between social groups and not just between social classes.

The bottom line is that economic conflicts underlying political conflicts, although Karl Marx himself admitted relative autonomy of the political superstructure.

Rafael Pla-Lopez considers society as a finite set of social behaviors with conflicting norms. The number of social behaviors available of a society increases with the increase of its dimension. So, studying human social evolution returns to the study of social behaviors evolution. In this work, we define social behavior as a set of values, beliefs, norms, customs, rules and codes that socially defines a group of people. In our model, social behaviors are characterized by a satisfaction capacity and a repressive capacity. In each society, each social behavior represses the norms of other social behaviors except a particular theoretical social behavior available for societies with dimension $m = 4$ that Rafael Pla-Lopez called "Free Scientific Society". This theoretical social behavior is characterized by a full satisfaction capacity and without initial repressive capacity (Pla-López 1989).

3 Artificial Society: Agent-Based Social Simulation

In an artificial society, the model is a multi-agent system: a set of autonomous agents that operate in parallel and that communicate with each other. Agent-based social simulation as a computational approach has-been largely used to explore and understand social phenomena thanks to (i) the agent social nature (ability to interact, communicate and collaborate with other agents), and (ii) its ability to detect emergent complex phenomena (Nemiche et al. 2013).

Sugarscape model built by Epstein and Axtell is a good example of an agent-based model that simulates an artificial society in which agents move over a grid of cells. Each cell has a renewable amount of sugar. The agents must consume sugar according to their metabolisms (metabolic rate, units of sugar the agent burns per time-step) for surviving. The agents move to the unoccupied cells with the greatest amount of sugar in their vision (vision rate, which is the maximum number of cells the agent can see in each of the four principal lattice directions: north, south, east and west). The agents accumulated sugar wealth is increased by the sugar collected and deceased by the agent's metabolic rate. The agent dies when its sugar wealth is zero. Whenever an agent dies it is replaced by a new agent of age 0 placed on a randomly chosen unoccupied cell (Epstein and Axtell 1996; Izquierdo et al. 2009).

Epstein and Axtell present a series of elaborations of Sugarscape model to illustrate various social phenomena. These models illustrate that:

- Agents that start in the most fertile areas and with high vision are those who accumulate wealth quickly. Then, by accumulation effect, the rich get richer and the poor even poorer
- From an equal distribution of sugar, the simulation evolves into a very unequal distribution of wealth; in which a minority of agents (with high vision rate) accumulates a wealth more than the average while the majority just has enough to survive (or dies).

Another important agent-based model in the social science is Axelrod's model of dissemination of culture (Axelrod cultural model). This model was motivated by the question: "If people tend to become more alike in their beliefs, attitudes and behaviors when they interact, why do not all such differences eventually disappear"? Axelrod's model has been the subject of several studies on cultural evolution with implications for issues such as state formation and social inclusion (Axelrod 1997). In this model, each cell represents a stationary individual's culture characterized by a set of f features, or cultural dimensions. Each feature composed by a set of q traits, which are the alternative values the feature may have. All agents have the same value for features, and all features have the same value traits. The individual culture is represented by a vector of f variables, where each variable takes an integer value in the set $\{0,1,..,q-1\}$. The model starts with random individual cultures. The parameter q model the initial cultural variety in the system (Axelrod 1997).

In each time-step, Agents interact according to the following rules:

- One agent A (active) is selected at random.
- One of agent A's neighbors, denoted agent P (passive), is selected randomly.
- Agents A and P interact with probability equal to their cultural similarity n_{AP}/f, where n_{AP} denotes the number of cultural features for which agents A and P has the same trait. The interaction consists in that active agent k selects at random one of the f - n_{AP} features on which the two agents differ, and copies the passive agent r's trait. In this way, agent A approaches agent P's cultural interests (Izquierdo et al. 2009).

The process outlined above continues until no cultural change can occur. This happens when every pair of neighboring agents have cultures that are either identical or completely different (Axelrod 1997; Izquierdo et al. 2009).

Axelrod's model illustrates how local convergence can generate global polarization in terms of stable regions of differing culture. Simulations show that the number of multicultural regions decreases with the number of features f in the culture, increases with the number of alternative traits q per feature and decreases with the range of interaction (Axelrod 1997; Izquierdo et al. 2009).

4 Model Description

In this section we present an extended and modified version of Rafael Pla-Lopez Social Evolution Model. We simulate social evolutions of N mobile artificial societies/Agents initially randomly distributed in a bi-dimensional grid of cells.

The Fig. 1 shows the basic structure of this model. Each society/Agent is composed of a set of social behaviors. The number of social behaviors available for a society depends on its dimension. Social behavior is modeled by a multidimensional vector $B = (B_m, \ldots B_2, B_1)$ of binary features $B_i \in \{0, 1\}$ where m represents the agent dimension. For example, if the dimension of an agent is 3 (three bits) then the social behaviors available for this agent are ***(0,0,0), (0,0,1), (0,1,0), (0,1,1), (1,0,0), (1,0,1), (1,1,0), and (1,1,1)***.

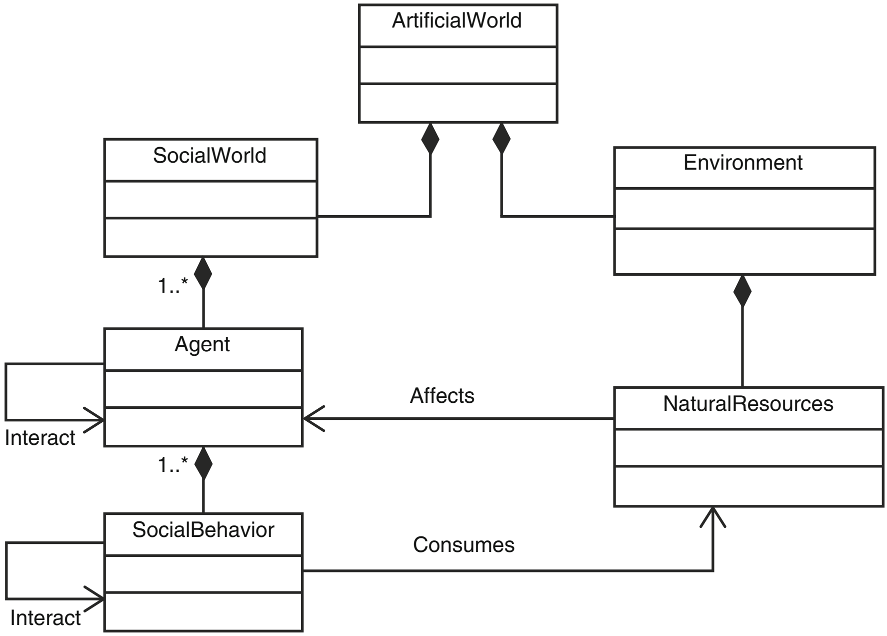

Fig. 1 Computational objects that compose the model (inspired from Cioffi-Revilla et al. 2007)

In the simulations, the dimension $\boldsymbol{m}$ takes values in the set $\{\boldsymbol{1,2,3,4}\}$. At the initialization ($\boldsymbol{t}=\boldsymbol{0}$) all the agents start with the same dimension $\boldsymbol{m}=\boldsymbol{1}$ (primitive society); this dimension increases over time under some conditions from 1 to the maximum value 4 in an autonomous way for each agent.

With the dimension increase we model the technological progress; the dimension $\boldsymbol{m}=\boldsymbol{2}$ can be interpreted by the agricultural revolution, $\boldsymbol{m}=\boldsymbol{3}$ by the industrial revolution and $\boldsymbol{m}=\boldsymbol{4}$ by a technological revolution.

4.1 The Environment Sub-model

The environment in which the agents evolve is a discrete spatial grid with dimensions $\boldsymbol{X}\times\boldsymbol{Y}$. Each cell $\boldsymbol{(x,y)}$ is defined by the current level of natural resources $\boldsymbol{K^t(x,y)}\in\boldsymbol{R}+$ and a maximum level $\boldsymbol{K_{max}}\in\boldsymbol{R}^*+$ (parameter, in this version is constant for all cells). This level will be increased every time-step following a fixed value $\boldsymbol{\rho}$ (natural resource growth rate, parameter constant of all cells) up to the $\boldsymbol{K_{max}}$ (maximum level of natural resources), and will be decreased if the agents consume them. In this model agents consume resources for satisfaction and repression. At the initialization, each cell $\boldsymbol{(x,y)}$ starts with a random initial level of resources $\boldsymbol{K^0(x,y)}\in\boldsymbol{R}+$ between $\boldsymbol{0}$ and $\boldsymbol{K_{max}}$.

When an agent occupies a cell ***(x,y)***, the value ***K(x,y)*** is updated as (Nemiche et al. 2013):

$$K^{t+1}(x,y) = max\left\{K^t(x,y) + \rho.K^t(x,y) - \left(CS^t + CR^t\right), K_{max}\right\}$$

where CS^t is the consumption of resources for satisfaction by the agent at time-step **t,** while CR^t is the consumption of resources for repression by the agent at time-step **t**.

In this model, a cell ***(x,y)*** only can be occupied by one agent at time-step ***t***.

When a cell ***(x,y)*** is unoccupied, the value of ***K(x,y)*** increases under following formula (Nemiche et al. 2013):

$$K^{t+1}(x,y) = max\left\{K^t(x,y) + \rho.K^t(x,y), K_{max}\right\} \tag{1}$$

4.2 Agents

This model is initially populated by ***N*** Agents located at random spatial coordinates ($N < X.Y$). Reminding that agents in this model represent artificial societies and each society is composed of a finite number of social behaviors in conflicting norms. En each time-step, each social behavior calculates its satisfaction/goal function:

4.2.1 Satisfaction Function

At each time-step ***t***, each social behavior ***B*** of each agent ***A*** evaluates its satisfaction according to the following formula:

$$S^t{}_A(B) = SC(B) \, . \left(1 - SR^t{}_A(B)\right) \tag{2}$$

where ***SC(B)*** is the satisfaction capacity of social behavior ***B***, and $SR^t{}_A(B)$ is the Social Suffered repression by the social behavior ***B*** of the agent ***A*** at the time-step ***t*** (Nemiche et al. 2013; Nemiche and Pla-Lopez 2003, 2000; Nemiche 2002; Pla-Lopez 2007, 1989, 1988; Pla-Lopez and Nemiche 2002).

We observe that, the satisfaction function of a social behavior ***B*** of an agent ***A*** at time-step ***t*** depends on:

- Its initial satisfaction capacity ***SC(B)*** (Internal factor);
- Its Social Suffered repression $SR^t{}_A(B)$ (external factor/social context).

If $SR^t_A(B) = 1$ (high suffered repression) then $S^t_A(B) = 0$; i.e. high values of Social Suffered repression by ***B*** decrease its satisfaction/goal.
If $SR^t_A(B) = 0$ (absence of Social Suffered repression) then $S^t_A(B) = SC(B)$; i.e. the satisfaction/goal of ***B*** depends only on its satisfaction capacity.

Now let's explain how to calculate the satisfaction capacity (internal factor) and the Social Suffered repression (external factor). We want that the satisfaction capacity of social behavior ***B*** increases with number of included properties between

Table 1 Satisfaction capacity of social behaviors

B (Binary representation)	B (Hexadecimal representation)	SC(B)
(0,0,0,0)	0	0
(0,0,0,1)	1	0.25
(0,0,1,0)	2	0.25
(0,0,1,1)	3	0.5
(0,1,0,0)	4	0.25
(0,1,0,1)	5	0.5
(0,1,1,0)	6	0.5
(0,1,1,1)	7	0.75
(1,0,0,0)	8	0.25
(1,0,0,1)	9	0.5
(1,0,1,0)	A	0.5
(1,0,1,1)	B	0.75
(1,1,0,0)	C	0.5
(1,1,0,1)	D	0.75
(1,1,1,0)	E	0.75
(1,1,1,1)	F	1

values ***0*** and ***1***. Tanking in consideration the binary representation of ***B*** a simple formula is

$$SC(B) = \left(\Sigma^{4}{}_{i=1}B_i\right) \;/\; 4 \tag{3}$$

In Table 1 we observe that the social behaviors ***B* = *(1), (1,1), (1,1,1)*** and ***B* = *(1,1,1,1)*** have the greatest satisfaction capacity in their dimensions.

4.2.2 Social Suffered Repression Function Used as a Mechanism for Social Change

Social suffered repression by a social behavior is considered as a negative influence (cause a satisfaction decrease) received by this social behavior from the other social behaviors of its neighborhood (von-Neumann neighborhood).

The equation used to calculate the Social Suffered repression by the social behavior ***B*** of the agent ***A*** at time-step ***t*** is:

$$\begin{aligned} SR^{t}{}_{A}(B) &= \left(\Sigma_{A'\in VA}\Sigma_{B'\neq B}\, p^{t}{}_{A'}\left(B'\right).RC^{t}{}_{A'}\left(B'\right).\ Imp\left(A' \to A\right)\ SD\left(B,\ B'\right)\right)/s \\ SR^{t}{}_{A}(B) &= 1\ if\quad SR^{t}{}_{A}(B) > 1 \end{aligned} \tag{4}$$

where ***s*** is the number of active agents in the neighborhood (V_A) of the agent A;

V_A is the von-Neumann neighborhood of range ***r*** (***r*** is a parameter of the model, see Fig. 2) (Nemiche et al. 2013). Note that $A \in V_A$

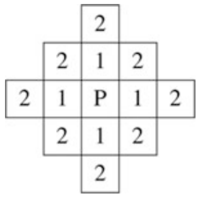

Fig. 2 Von-Neumann neighborhood of range $r = 2$ (Manhattan distance r = 2, wikipedia)

$p^t{}_{A'}(B')$ is the probability/weight of the social behavior B' of the agent A' at time-step t.
$RC^t{}_{A'}(B')$ is the repressive capacity of the social behavior B' of the agent A' at time-step t;
$Imp(A' \rightarrow A)$ is the impact coefficient of the agent A' over the agent A;
$SD(B, B')$ is the social distance between social behaviors B and B';

The order of social behaviors apparition is: firstly the appearance of social behaviors with one feature, secondly with the technological progress new social behaviors with two features appear, thirdly social behaviors with three features appear and finally social behaviors with four features appear. We think that the social distance between two social behaviors B and B' increases when the differences are in the features with small index:

$$SD(B, B') = \left(\Sigma^4{}_{i=1} w_i \left|B_i - B'_i\right|\right)/SD_{max} \tag{5}$$

with $w_i = w_{i-1}/2$ for $i = 2,3,4$

$$w_1 = 8$$

where SD_{max} is the maximal social distance between two social behaviors:

$$SD_{max} = SD\left((0,0,0,0),(1,1,1,1)\right) = 8 + 4 + 2 + 1 = 15$$

The impact of an agent A' over agent A calculation is seen in Eq. 5.

$$Imp^t(A' \rightarrow A) = \sum\nolimits_B p^t{}_{A'}(B)\,.\,imp\left(B, d(A', A)\right) \tag{6}$$

where $d(A', A)$ is the distance between A' and A;
$imp(B, d(A', A))$ is the impact of the social behavior B at the distance $d(A', A)$.

4.2.3 Probability/Weight Calculation: Learning Process

Each social behavior B of an agent A over time in updates its accumulated memory $F^t{}_A(B)$.

The accumulated memory $F^{t+1}{}_A(B)$ value of social behavior B of agent A at time-step $t + 1$ is calculated as a function of his former value $F^t_A(B)$ at time-step t.

This function depends also on how positively (or how negatively) social behavior $\boldsymbol{B}$ in the agent $\boldsymbol{A}$ evaluated the interactions with the other social behaviors in the neighborhood $\boldsymbol{V_A}$. In formula (Pla-López 1988):

$$\boldsymbol{F^{t+1}}_A(\boldsymbol{B}) = \boldsymbol{F^t}_A(\boldsymbol{B}) + \boldsymbol{\lambda}\left(\boldsymbol{S^t}_A(\boldsymbol{B}) - <\boldsymbol{S^t}_A>\right)$$

$$\text{If} \quad \boldsymbol{F^{t+1}}_A\,(\boldsymbol{B}) < \boldsymbol{0} \textbf{ then } \boldsymbol{F^{t+1}}_A\,(\boldsymbol{B}) = \boldsymbol{0} \tag{7}$$

where $\boldsymbol{\lambda}$ = change rate parameter;

$$<\boldsymbol{S^t}_A> = \left(\Sigma_{A'\in VA}\Sigma_{B'}\,\boldsymbol{p^t}_{A'}\left(\boldsymbol{B'}\right)\ \boldsymbol{S^t}_A(\boldsymbol{B'})\right) / \left(\Sigma_{A'\in VA}\Sigma_{B'}\,\boldsymbol{p^t}_{A'}\left(\boldsymbol{B'}\right)\right)$$

$$\text{(weighted mean)} \tag{8}$$

The probability/weight of social behavior $\boldsymbol{B}$ in the Agent $\boldsymbol{A}$ at the time $\boldsymbol{t}$ is obtained as:

$$\boldsymbol{p^t}_A(\boldsymbol{B}) = \left(\boldsymbol{F^t}_A(\boldsymbol{B})\right) / \Sigma_{B'}\boldsymbol{F^t}_A\left(\boldsymbol{B'}\right) \tag{9}$$

$\sum_{B'}\boldsymbol{F^t}_A\,(\boldsymbol{B'}) = \boldsymbol{M^t}_A$ is the accumulated memory in the agent $\boldsymbol{A}$ at the time $\boldsymbol{t}$;

At the initialization $\boldsymbol{F^0}_A(\boldsymbol{B}) = \boldsymbol{R^0}_A$ represents the level of natural resources available in the cell occupied by the agent $\boldsymbol{A}$.

We say that a social behavior $\boldsymbol{B}$ dominates in the agent $\boldsymbol{A}$ at the time-step $\boldsymbol{t}$ if $\boldsymbol{p^t}_A(\boldsymbol{B}) > \boldsymbol{0.5}$. In the simulation interface, in each step-time, we display only the hexadecimal representation of dominants social behavior of each agent. We call pseudo-state of an agent $\boldsymbol{A}$ at time-step $\boldsymbol{t}$ the social behavior B that has $\boldsymbol{p^t}_A(\boldsymbol{B}) > \boldsymbol{0.5}$. If all social behaviors of an agent $\boldsymbol{A}$ at time-step $\boldsymbol{t}$ their probability is strictly less than $\boldsymbol{0.5}$ we call this state "intermediate pseudo-state", in the simulation interface it is represented by the symbol "-".

4.2.4 Repressive Capacity Calculation

The repressive capacity of a social behavior $\boldsymbol{B}$ of an agent $\boldsymbol{A}$ evolves from the initial repressive capacity $\boldsymbol{RC^0(B)}$ to its social suffered repression with a delay Ta:

$$\boldsymbol{RC^{t+1}}_A(\boldsymbol{B}) = \boldsymbol{RC^t}_A(\boldsymbol{B}) + (\Delta\boldsymbol{t}/\boldsymbol{Ta})\,.\left(\boldsymbol{SR^t}_A(\boldsymbol{B}) - \boldsymbol{RC^t}_A(\boldsymbol{B})\right) \tag{10}$$

$\boldsymbol{RC^0}_A\,(\boldsymbol{B}) = \boldsymbol{RC^0}\,(\boldsymbol{B})$ the initial repressive capacity don't depends of $\boldsymbol{A}$.

$\boldsymbol{Ta}$ is a parameter of the model with which we can simulate different rhythms of repression adaptation.

Each agent $\boldsymbol{A}$ at time-step $\boldsymbol{t}$ consumes natural resources of its cell for repression ($\boldsymbol{CR}$) and satisfaction ($\boldsymbol{CS}$) according to:

$$\boldsymbol{CR^t{}_A} = \sum_B \boldsymbol{p^t{}_A} (\boldsymbol{B}) \,.\, \boldsymbol{RC^t{}_A} (\boldsymbol{B}) \tag{11}$$

$$\boldsymbol{CS^t{}_A} = \sum_B \boldsymbol{p^t{}_A} (\boldsymbol{B}) \,.\, \boldsymbol{SC} (\boldsymbol{B}) \tag{12}$$

This model can simulate the ecological holocaust in which the evolution ends due to the resources exhaustion (situation of high consumption of resources for satisfaction and repression).

The initial repressive capacity $\boldsymbol{RC^0}$ is the second attribute (static property) that characterizes social behaviors. We remind that the fist attribute (static property) is the satisfaction capacity.

The initial repressive capacity of a social behavior B depends on its force $\boldsymbol{\mu(B)}$ and its ferocity $\boldsymbol{\nu(B)}$. The initial repressive capacity of a social behavior is equal to zero when its force or its ferocity is equal to zero. The simple formula is the product (Rafael Pla-Lopez):

$$\boldsymbol{RC^0} (\boldsymbol{B}) = \boldsymbol{\mu} (\boldsymbol{B}) \,.\, \boldsymbol{\nu} (\boldsymbol{B}) \tag{13}$$

which guarantees that $\boldsymbol{RC^0(B) = 0}$ if $\boldsymbol{\mu(B) = 0}$ or $\boldsymbol{\nu(B) = 0}$

We think that the force of a social behavior $\boldsymbol{B}$ increases with its dimension and with its included attributes; in a way that a social behavior with a great dimension possesses a great force. Taking into consideration the binary representation of social behavior, the simple function that satisfies these conditions is the decimal representation of the social behavior $\boldsymbol{B}$; i.e. $\boldsymbol{\mu(B) = (\sum_i 2^i.Bi)}$. So, $\mu(\mathrm{B}) \in \boldsymbol{[0,15]}$. In order to normalize the values of the force we consider:

$$\boldsymbol{\mu} (\boldsymbol{B}) = \left(\sum_i \boldsymbol{2^i.Bi}\right) / \,\mathbf{15} \tag{14}$$

We assume that the ferocity of a social behavior decreases for the more advanced social behavior $\boldsymbol{B}$ $\boldsymbol{(B4 = 1)}$, and increases for the social behaviors that are less advanced ($\boldsymbol{B4 = 0}$). The formula of the ferocity in this model is (see also Fig. 3):

$$\boldsymbol{\nu} (\boldsymbol{B}) = \left(\boldsymbol{1} - \left(\left(\left(2.\sum_i \boldsymbol{2^i.Bi}\right)/\mathbf{15}\right) - \boldsymbol{1}\right)\right)^{\boldsymbol{2}} \tag{15}$$

As can be seen from Table 2 the social behavior $\boldsymbol{B = (0,1,1,1) = 7}$ has the greatest initial repressive capacity in its dimension ($\boldsymbol{m = 3}$), the social behavior $\boldsymbol{B = (1,1,1,1) = F}$ has an initial repressive capacity equal to zero (without initial repression) and a high satisfaction capacity. This is what Rafael Pla-Lopez called **Free Scientific Society** (theoretical social behavior).

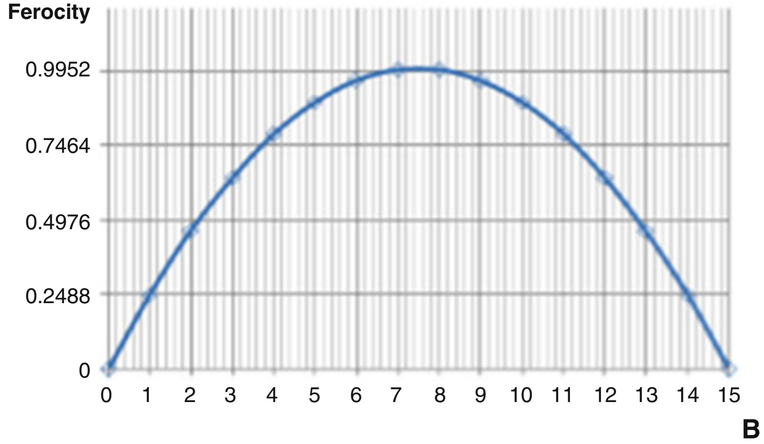

Fig. 3 Graphic representation of the ferocity function (source Nemiche et al. 2013)

Table 2 The values of force, ferocity and initial repressive capacity of social behaviors

B (Binary representation)	B(Hexadecimal representation)	μ(B)	ν(B)	RC^0(B)
(0,0,0,0)	0	0	0	0
(0,0,0,1)	1	0.066667	0.248889	0.016593
(0,0,1,0)	**2**	0.133333	0.462222	0.06163
(0,0,1,1)	**3**	0.2	0.64	0.128
(0,1,0,0)	4	0.266667	0.782222	0.208593
(0,1,0,1)	5	0.333333	0.888889	0.296296
(0,1,1,0)	**6**	0.4	0.96	0.384
(0,1,1,1)	**7**	0.466667	0.995556	0.464593
(1,0,0,0)	8	0.533333	0.995556	0.530963
(1,0,0,1)	9	0.6	0.96	0.576
(1,0,1,0)	A	0.666667	0.888889	0.592593
(1,0,1,1)	B	0.733333	0.782222	0.57363
(1,1,0,0)	C	0.8	0.64	0.512
(1,1,0,1)	D	0.866667	0.462222	0.400593
(1,1,1,0)	**E**	0.933333	0.248889	0.232296
(1,1,1,1)	**F**	1	0	0

4.2.5 Technological Progress

We simulate the technological progress of agent ***A*** with the increase of its dimension. The agent dimension increases one unit (in the simulation from ***1*** to ***4***) with a high probability when the value of its accumulated memory is approaching to a progress parameter ***prg*** (parameter of the model) (Nemiche et al. 2013; Nemiche and Pla-Lopez 2003, 2000; Nemiche 2002; Pla-Lopez 2007, 1989, 1988; Pla-Lopez and Nemiche 2002).

4.2.6 Reproduction and Death of Agents

In this model an agent $\boldsymbol{A}$ can die in two manners: (i) natural death, when its accumulated memory $\sum_B {F^t}_A\,(B)$ is approaching to the life expectancy value ***Thanatos*** (parameter of the model) and (ii) dissatisfaction death, when its accumulated memory is approaching to the value $\boldsymbol{0}$ $\left(\sum_B {F^t}_A\,(B) = 0\right)$ or when the level of natural resources of the cell occupied by $\boldsymbol{A}$ is zero.

The reproduction in this model is also produced in two ways (i) by relay, when an agent $\boldsymbol{A}$ dies naturally the relay is immediately produced with the appearance of a new agent 'neophyte' in the cell previously occupied by the agent $\boldsymbol{A}$ and (ii) by recuperation, when an agent dies by dissatisfaction; the recuperation mechanism takes some time-steps. We would facilitate the recuperation of the unoccupied cells previously predominated by less advanced social behaviors (Nemiche et al. 2013; Nemiche and Pla-Lopez 2003, 2000; Nemiche 2002; Pla-Lopez 2007, 1989, 1988; Pla-Lopez and Nemiche 2002).

4.2.7 Agent Mobility: Migration

In this version, the agents are mobile. They can move/migrate for two reasons (i) when its natural resources are unfavorable; its resource capacity (K^t_A) is less or equal to a threshold S_m ($K^t_A < S_m$). S_m is a parameter of the model and (ii) when the social suffered repression of its social behaviors is approaching to the value 1. In this situation the agent moves to a free cell with more natural resources in its social neighborhood. In this model we simulate only the forced migration.

The migration is another mechanism that makes it possible for agents to survive in war and adverse natural situations, looking for free cells in its neighborhood with more resources. An agent $\boldsymbol{A}$ can move/migrate only to a cell (***x,y***) within its perceptions. An agent $\boldsymbol{A}$ candidate for the migration at the time-step $\boldsymbol{t}$, selects the first item (cell) in its table of resources perceptions. It is possible to have several agents who wish to move to the same cell. The management of this conflict consists of giving advantage to the agents with the biggest dimensions and in a random order in case of equal dimension. When the agent $\boldsymbol{A}$ is moved to this cell, at time-step $\boldsymbol{t}$, the model updates its position, its resources and its perceptions, and the system deletes this cell from the resources perceptions of other agents (Nemiche et al. 2013).

5 East–West Divide (Collectivist Versus Individualist)

According to Maurice Godelier (1970), we could describe two main lines of social evolution: one which we could call "Occidental" had gone through phases: slavery, western feudalism, and capitalism with a significant role of the private property. In the second line ("Orient") the sense of collectivism dominated in all the phases beginning with what was called Asiatic mode of production and eastern feudalism and state socialism. Only at the end of twentieth century the two lines of evolution converge to which is called Globalized capitalism (globalization).

In order to simulate the East–West divide Rafael Pla-lopez and Mohamed Nemiche have supposed that the first feature ($\boldsymbol{B_1}$) of social behavior distinguishes between social individualistic and collective behaviors. Individualistic behaviors have $\boldsymbol{B_1 = 1}$ and collective behaviors have $\boldsymbol{B_1 = 0}$. As can be seen from Table 3 we have two families of social behaviors (Nemiche and Pla-Lopez 2003, 2000):

Note that in this model, the impact function ***Imp*** affects directly the suffered repression. Rafael Pla-Lopez and Mohammed Nemiche consider that there are two different impact functions: one for the individualist social behaviors and the other one for the collective social behaviors (Engels 1884). This differentiation in the impact function is the principal cause of the East-West divide:

1. The impact function of individualist social behaviors is $\boldsymbol{0}$ when the distance is equal to $\boldsymbol{0}$ (in self-society); that is to say, the individualist social behaviors does not repress the other social behaviors in self-agent (individual property), but they repress all social behaviors of the neighborhood agents.
2. The impact function of collective social behavior reaches its maximum in the self agent (collective property) and decreases with distance.

The Figs. 4 and 5 are a possible representation of the individualist and collective social behaviors respectively:

From the Figs. 4 and 5 we observe that the collective social behaviors repress in the agent more than its neighborhood. However, social individualistic behaviors repress in its neighborhood but not in the agent.

Table 3 Individualist and collective behaviors

Social Individualist behaviors	Social Collective behaviors
(0,0,0,1)	(0,0,0,0)
(0,0,1,1)	(0,0,1,0)
(0,1,0,1)	(0,1,0,0)
(0,1,1,1)	(0,1,1,0)
(1,0,0,1)	(1,0,0,0)
(1,0,1,1)	(1,0,1,0)
(1,1,0,1)	(1,1,0,0)
(1,1,1,1)	(1,1,1,0)

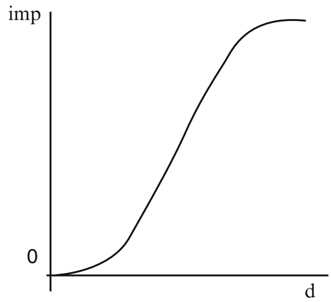

Fig. 4 Graph of the impact function of an individualist social behavior in the neighborhood

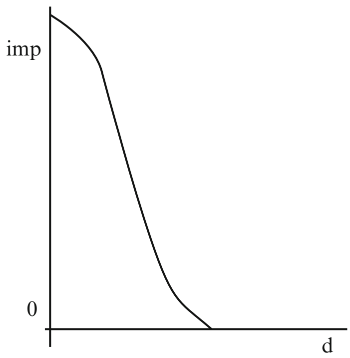

Fig. 5 Graph of the impact function of a collective social behavior in the neighborhood

A possible interpretation of the most important social behaviors of the Fig. 6:

B* = *(0,0,0,0) as the primitive society
B* = *(0,0,0,1) as the social behavior of "Slavery"
B* = *(0,0,1,0) as the social behavior of "Asiatic mode of production"
B* = *(0,0,1,1) as the social behavior of "Western Feudalism"
B* = *(0,0,1,0) as the social behavior of "Eastern Feudalism"
B* = *(0,1,1,0) as the social behavior of "State Socialism"
B* = *(0,1,1,1) as the social behavior of "Capitalism"
B* = *(1,1,1,1) as the social behavior of "Free Scientific Society"

6 North–South Divide (Fast Growing Technology Versus Slow Growing)

Rafael Pla-Lopez considers that the social evolution in the north has been faster than the south social evolution. He supposes that the agents situated in the north have a life expectancy (***Thanatos***) bigger than the south agents. So, the life expectancy will be a function that varies from north to south instead of considering it constant for all agents. The technological progress produces in the South through a Cultural and Technological Diffusion which can simulate the colonialism (Pla-Lopez 2007).

7 Preliminary Results

The model is implemented in java language; with its simulation we have obtained several types of social evolutions. In this chapter, we announce only three social evolutions:

- Perpetuity of the globalization with the repressive social behavior: evolutions where all the active agents end dominated by the repressive social behavior $\boldsymbol{B} = \boldsymbol{(0,1,1,1)} = \boldsymbol{7}$; i.e. repressive globalization state. The perpetuity of the capitalist globalization according to Fukuyama (Fukuyama 1995) can be a possible interpretation of this result.
- Overcoming of the repressive globalization with another globalization with the free scientific society $\boldsymbol{B} = \boldsymbol{(1,1,1,1)} = \boldsymbol{F}$: evolutions where the repressive globalization is overcome by another free scientific globalization ($\boldsymbol{B} = \boldsymbol{F}$), characterized by a great satisfaction and without initial repressive capacity.
- Ecological holocaust: death of all the agents due to exhaustion of resources (The collapse of the global ecology) or dissatisfaction.

These simulations were obtained using the parameters values of the former version. We need perhaps to re-calibrate these parameters in order to get an accurate simulation of the real social evolution of humanity until the present time, through different phases and with a different evolution between both East-West and North-South.

8 Conclusion and Perspectives

This chapter describes a generic model of social behaviors change. Modeling and simulation of soft systems, where the human factor is crucial, is a complex task. For lack of historical data we will only proceed to a qualitative validation of our model which is based on the historical schema presented in the Fig. 6. The presented results are a first stage of research that should be continued with a detailed sensitivity analysis. When we do this qualitative validation, we will be able to study the conditions and the possibilities of later local emergency of ways to a free scientific society $\boldsymbol{(1,1,1,1)}$ in front of “capitalism forever” or ecologic holocaust, and if this alternative social system can develop first in the South or in the North. Also, in the case of ecological holocaust, we would be able to forecast if this would begin in the North or in the South. This model can also help to understand the migration process (Pla-Lopez 2007).

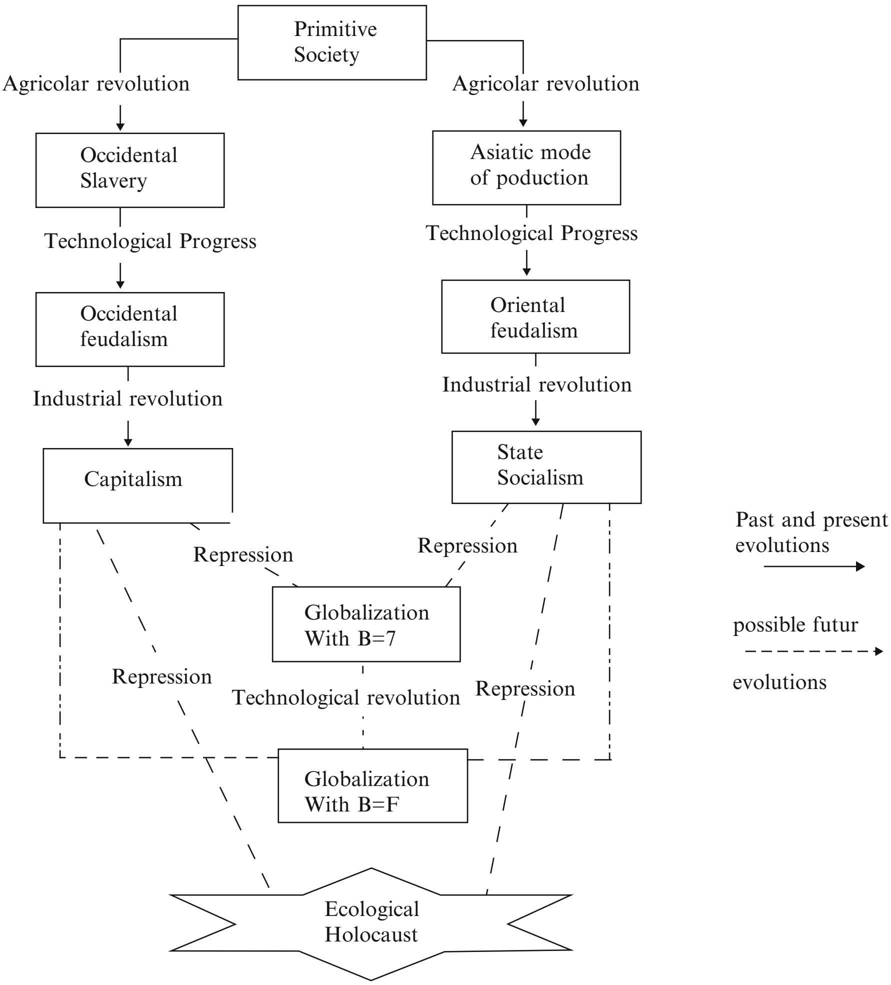

Fig. 6 East–West divide and some possible future evolutions (source Nemiche 2002)

Appendix

The model is implemented in java source code

1. Class ***SocialVisualizer*** that implements a graphical interface as a grid to visualize the dynamic model
2. Class ***SocialModel*** that implements the two-layer structure of Model (Resources and agents). The main tasks (methods) are:

   Initialization:
   - Initialize "constants" (parameters of the model) from configuration file

- Create resources
- Initializes resources
- Create agents (list of Societies Live)
- Initializes agents (Initializes memory, probability, Repressive Capacity and Suffered Social Repression)

Main loop

```
public void run() {
       for ( T=0 ; T <= Tmax ; T += deltaT ) {
             for ( nAgent = 0;   nAgent < listAgent.length;
                    nAgent ++) {
                    listAgent[nAgent].updateAgent(listAgent);
             }
             if ( getNumberAgentLive() == 0 ){
                    fLog.println("End: are not living systems.");
                    break;
             }
             migration();
             updateResources();
             sleep(delay);
    }
  }
```

3. Class ***Agent*** that implements dynamics and evolution of internal agent processes. The main methods are:

Initialization:

```
public void init() {
                 initAccumulatedMemory();
                 initForce();
                 initFerocity();
                 initSatisfactionCapacity();
                 initRepressiveCapacity();
    }
```

Update Agent:

```
public void updateAgent( Agent []  listAgents )  {
        if( this.isLive() ){
                updateProbability();
                updateSocialSufferedRepression(listAgents);
                updateRepressiveCapacity();
```

(continued)

```
                updateSatisfactionFunction();
                updateAccumulatedMemory();
                updateResourceAgent();
                if( ! this.isDeath() ){
                     checkProgress ();
                }
           }else{
                    checkRecuperation();
           }
    }
```

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Understanding Social Systems Research

Louis Klein

Abstract Social complexity seems to be the number one critical success factor not only for project management or organisational development but for any attempt to govern the Anthropocene and bring about successful systemic change to meet climate change, poverty and political conflict to name but a few.

Social systems research seems to be unnecessarily underrated since it developed into a discipline which has more to offer than metaphors of swarm intelligence and self-organisation. On the contrary, constructivism facilitated the epistemological turn shifting from objectivity to functional adequacy as the central research criterion, and the digital transformation as well as gamification paved the path for a convincing new generation of systems analytics enlightening the political and cultural aspects of social complexity in an amazing fashion.

Systemic inquiry based on a praxeological understanding of action research opens new possibilities for social design impact evaluation and social innovation assessment. The next society needs to be systems savvy. Social systems research already shows how the next society could successfully meet its own social complexity.

1 Introduction

Understanding social systems research is a much bigger challenge than the scientific community is currently willing to acknowledge. And on the same instance social systems research is key for every meaningful change in the twenty-first century.

Social complexity (Sect. 2) is more than a token for failing projects and a placeholder for human deficiencies. Turning to social complexity brings political and cultural aspects of social systems into sight and challenges the narrow perspective of sciences, objectivity and complexity reduction. Social systems (Sect. 3) are autopoetic, meaning processing systems. They refer not only to empirically observable actualities but to hidden possibilities as well. Observing communication

L. Klein (✉)
The Systemic Excellence Group, Berlin, Germany
e-mail: l.klein@segroup.de

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and the processes of sensemaking and meaning creation in the form of stories and narratives is key to any understanding of social systems. Social systems research based on systemic inquiry (Sect. 4) needs to account for this. Social systems are systems in itself and for itself. Acknowledging this very nature of social systems marks an epistemological turn in social systems research.

Social systems research (Sect. 5) is inevitably a praxeological endeavour. It is a human activity, hence a human activity system in itself embedded social systems. This creates an extra challenge for problem structuring and research design as a learning circle following the heuristic of exploring-mapping-trading. Systems analytics (Sect. 6) prove again that with new challenges there come new opportunities. Especially mapping in social systems research can computationally be developed in dynamic, interactive simulations which serve as a source of insight themselves and allow for social design impact evaluation.

Becoming systems savvy (Sect. 7) shall be a call for the twenty-first century. Social systems research can serve as a conveyor fostering systems literacy allowing for change towards better organisations and institutions in the next society.

2 Social Complexity

Social complexity is a problem. That is what we have learnt. It is not people alone. It is how they interact. A focus on interaction however may again be misleading for researching social systems (Klein 2012). If we observe people interacting we are confronted with a lot of activity, but we are bound to miss the larger picture and the intrinsic complexity. Empirical observation of human activity systems may tell us a lot about what is actually happening, empirically, after the fact. This however misses the essence. We may want to acknowledge that any human activity is first of all not determined. People are for people a constant source of uncertainty. Their possible behaviour, their behavioural contingency, remains a challenge (Luhmann 1984). The key strategy to reduce and handle this uncertainty is to build and process expectations about what could happen. However, this is not trivial, but a source of systemic complexity.

Human activities are embedded in a field of expectations and this field of expectation is changing over time in relation to the actual activities and interactions that happen. In their interaction people will orientate their behaviour mutually on the other person's behaviour. And they will orient their behaviour mutually on their expectations of the other person's behaviour. And they will orient their behaviour mutually on their expectations of the other person's expectations. Beyond complicatedness it is complex because behaviour and expectation and expectations of expectations are mutually dependent and influenced. This is what Niklas Luhmann addresses as double contingency of behaviour and expectations (1984). It is like an equation with more than two unknown variables, hence it is complex and cannot be unambiguously solved. This sounds complicated. Every contemporary and up to date theory of social systems takes this into account (Luhmann 2013, 2012, 1984; Bourdieu 1979; Habermas 1981; Foucault 1971). However, the resolution of observation does not really account for the systemic dynamics of the embedment of any interaction into the emergent larger context of social systems.

Project management is a good example to illustrate the challenge. Project management is a discipline, a business practice that is codified and referenced by a disciplinary matrix of models, methods and instruments. The project management book of knowledge (PMBOK) guide issued by the Project Management Institute (PMI 2013), like the various competence baselines issued by the International Project Management Association (IPMA) focus on a body of knowledge that is facilitating a desired project management practice (Szalajko et al. 2016). Any approach of codifying a specific practice, however, is facilitated by the idea of reducing complexity, highlighting desirable practices and behaviour and ruling out other possible practices and behaviours. At the very heart of project management lies the reduction of complexity. Standardisation and codification made the success of project management. And then comes complexity (Whitty and Maylor 2009).

Project management fails on the human side. We may address communication deficiencies, team dynamics, leadership styles or many other phenomena. The mainstream of project management research is reproducing this insight over and over again. It is not the technical challenges; it is the people who put project success at risk. It is not the technology that makes our world so volatile (V), uncertain (U), complex (C), and ambiguous (A) as described in the concept of the VUCA world (Bennett and Lemoine 2014; Stiehm 2002). It is the people in the picture.

When the International Centre for Complex Project Management (ICCPM) was founded in 2008, complexity was introduced into the project management discourse as a token or a place holder for what needed to be understood, putting project management back to success. The initial research focus was especially on mega projects in the public domain and the major sponsor, the Defence Material Organisation of the Australian Army, were suffering from the malperformance of project management applied to sourcing new ships or aircraft. The majority of those mega projects in the public domain violated their schedules and budgets and failed to deliver the expected quality. Intensifying the research into technical complicatedness and the complexities of systems engineering did not further any improvement in project performance. In fact, all that brilliant research done on the behalf of the ICCPM revealed at a very early stage that the focus needed to be shifted away from technology towards the so called human aspect in project management.

Meeting the human aspect of change is the well-known critical success factor in the field of organisational development. Change for that matter requires vigorous project management as well. However, in the context of organisational development (OD) it became apparent at a very early stage that the human aspect is key to any possibilities of success. It is group dynamics, it is politics at work, it is stakeholder management, leadership, team building, communication and all those other aspects dealing with people at the human side of organisations. OD tapped into group dynamics and psychology, sociology and communication theory to enrich the understanding of change in organisations which then were to be understood as genuine social systems. It is not really a major insight that people at work exceed the

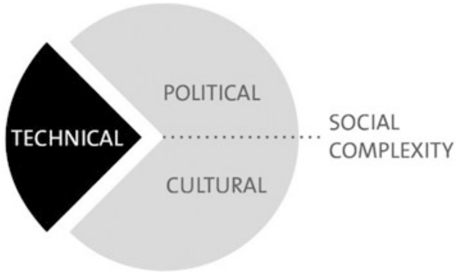

Fig. 1 TPC-model of social complexity

behavioural contingency of a job description. And even a situation where everybody was just doing diligent and dutifully his or her job, the interactional interplay creates dynamics and emergence which contribute to the embedding entity of the embedding social system, which bears qualities that cannot be traced back to the individual behaviour or even the dynamic interplay of interactions.

We see what we are prepared to see. This constructivist insight well-founded in the theory of observation became mainstream in a more anecdotal way. The impact however on social systems research cannot be underestimated. As an initial illustration Fig. 1 may serve the cause. Noel Tichy (1983) identifies three cardinal perspectives for the observation of organisations, a technical perspective (T), a political perspective (P) and a cultural perspective (C). The model suggests that especially in western societies we have a preference and thus a systemic bias for the technical perspective. Science and education focus on the technical perspective as the hard facts. Cultural and political issues are pushed over to the soft side. What we see is a systematic neglect of the aspects of human interaction. The political perspective looks at the micro politics of interaction wherein different interest and intentions are strategically introduced and processed in communication. It is not so much the larger political frame the TPC model is referring to. And in the same way it goes well beyond our everyday understanding of culture. The cultural perspective rather looks at the narrative frames of sensemaking (Weick 1995) and meaning creation (Luhmann 1984) which serve as paradigmatic references, giving orientation for individual behaviour. Addressing social complexity, we may use the TPC model combining the cultural and political perspective in contrast to the technical perspective. In this understanding we may say that we neglect two thirds of the pie (Fig. 1). Of course, for the TPC models accounts what holds true for all models, namely that they are rather not qualified as true or false but as more or less useful. And the TPC model proved to be tremendously useful and functional in shifting the observational perspective away from the observational routine and the focus on technology towards the two grounds which account for social complexity.

Meeting social complexity is a prerequisite for any kind of change. Understanding social systems starts with understanding social complexity and it may deepen the understanding of the impact of social design and may eventually lead to the possibility of systemic change (Klein 2013, 2010). And here we are back to project management. Science provided a lot of insight into all of the contemporary challenges, be it climate change, poverty or the digital transformation. The necessary change seems to fail either on the political side or the cultural side. And what holds true for the macro scale of the globe holds true as well for the micro scale of organisations, cities, regions, nations and football teams. It is about time to shift the focus towards social complexity and start to understand the systemic nature of social systems.

3 Social Systems

Social systems are emergent entities. They are bearing qualities which exceed the quality of the sum of its parts. This insight is not new and rather common sense. However, it puts an enormous challenge for any kind of research to find the right resolution level for any observation. We may ask what social systems look like and rely on empirical observations. What we accordingly see is quantifiable observations on the various levels and we can describe what is happening in any specific point in time. However, if we look at emergent systems we encounter what Heinz von Foerster called non-trivial machines (2002). It is nearly impossible to predict the further course of events by looking at a snapshot or even a time series from past to present. Looking for causal input output relationships misses the point. Hence any kind of statistical approaches and quantitative research in social systems is bound to fail or is producing meaningless data and conclusions.

The understanding of social systems rests best on a functional perspective. This is pursuing the questions of how systems tick. There is a well-trotted path of systems analytics which may be understood as a junction between stochastics and big data. Neuro-sociology ventures this path in its attempt to understand social systems (Baecker 2014; Schnabel 2012). However, it has a tendency to slide over to a perspective which treats social systems as populations of a more or less randomly interacting species. And although we see amazing advances in predicting behavioural patterns we do not really meet the contingency and complexity of social systems to come and change these very patterns and display surprisingly new behavioural traits.

Social systems cannot be reduced to behavioural patterns only. As Robert Musil so nicely put it in his novel The Men without Qualities (1930), human beings do not only sense reality, they have a sense for possibilities as well. And this very sense of possibility is something apart from their actual behaviour that human beings contribute to social systems in the medium of communication. Social systems hence are not only described by what is but also by its possibilities.

Meaning, as Niklas Luhmann puts it, is the unity of a distinction of actuality and possibility (1984). For Niklas Luhmann social systems are meaning processing systems. They are calculating not only what is but also what they regard as being possible. Luhmann's theory of social systems embarks on communication being the very element of social systems, not people, not human beings, not individuals. It is communication that has the capability of processing not only observations of facts and figures but also ideas of possibilities. Only in communication those things which are can be related to those things which seem possible but are not present at that very moment. Niklas Luhmann describes social systems as autopoetic systems (1984). They reproduce the elements out of which they consist out of the elements of which they consist. This describes the circular reinforcing loop which suggests turning to systems sciences and cybernetics to provide a robust theoretic foundation for any further consideration. In addition, distinction theory (Luhmann 2002; Simon 1993; Bourdieu 1979; Bateson 1972, 1979; Spencer-Brown 1969) offers substantial contributions, starting with the distinction of system and environment as the primary distinction that ignites systems theory. It immediately poses the questions how this initial or primary distinction comes into being and what is needed to produce it and to sustain it. It hands over to the functional perspective and asks for the interplay of elements which produce an emergent entity which is able to maintain its boundaries over time.

Social systems are systems in itself and for itself. It is not only the external observer who can identify a system as such, a system in itself. The marvellous things about autopoetic emergent systems is that they need to observe themselves to maintain their autopoetic existence. This puts an additional challenge to any attempt to understanding social systems. We are not only challenged with our understanding of social systems; we are challenged with the social system's understanding of being a social system. This leads to the epistemological challenge of the distinction between ontology and epistemology. It is necessary but not sufficient to understand what the system is. Hence any empirical approach tends to be futile in the end. We cannot evade the question asking for the conditions of the possibility of ourselves and of social system to understand what social systems are and what social systems could be. This is certainly not trivial and it throws us back to the initial epistemological conditions of observation.

Any observation is blind for itself being an observation and the distinction that is necessary to produce an observation as such. Heinz von Foerster refers to this challenge as the blind spot (2002) and suggests what is referred to as second order observations in the context of second order cybernetics. The ability and the willingness to observe observations is key and condition for the possibility of researching and understanding social systems. Bernhard Scott enriches this notion with his principles of observation (2009). According to these principles of observation, there is, to any given observation, always a level of more detail, always a bigger picture and always an alternative perspective. And this holds true not only for the external observer but also for any system observing itself. Social systems refer to themselves as activity systems. This is according to Niklas Luhmann the preferred level of observations of social systems to refer to themselves (1984). This cunningly evades the challenge to observe communication giving the volatile nature of communication which vanishes the moment it comes into existence. The focus on activities seems to provide an adequate resolution level for any investigation into social systems and allows to follow the trails of the organisational self-observation and self-description. And yet, knowing about the very nature of social systems as being emergent and autopoetic sense processing entities, we know that the references to activities is just producing an observable surface, a shadow of how social systems actually tick and click.

4 Systemic Inquiry

All what you can understand about systems is bound to systemic inquiry (Burns 2012; Collen 2003; Romm 2002; Churchman 1968). The term systemic inquiry indicates that research into systems and especially into social systems cannot be reduced to observations (Klein and Weiland 2014; Klein 2005). Inquiry carries the notion of interactive questioning and the idea that the essence of systems may be different to what occurs to the eye at first sight (Flyvbjerg 2001). Adding the term system to inquiry points into two directions. First, the inquiry bears in mind that it is especially the systemic qualities that make the social system. This is on the one hand the emergent interplay of the observable elements and secondly, that social systems do not only behave but that they process next to actualities possibilities in the medium of meaning. And second, systemic inquiry indicates that the very activity of inquiry will be processed as a disturbance or perturbation by the social systems in focus and hence systemic inquiry needs to take into account that it possibly changes the social system in focus (Klein and Kiehne 2006).

A social system observing itself as an activity system will describe itself in term of stories and narratives. This idea is easy to connect to and overlaps very much with our everyday experience. It nevertheless puts tremendous challenges to research into social systems (Jorgensen and Largacha-Martinez 2014; Boje 2007, 2001). To what extent can stories and narratives be the source for valid descriptions of social systems? It seems to be difficult to relate the scientific criteria of truth to the notion of stories. And this is where we need to shift from truth to functionality to provide an access to understanding social systems. If we try to understand social systems, we need to follow the logic of a social system which is not unfolding along scientific criteria of truth. It is unfolding along the pragmatic of functionality. The story in that respect can be true or false in the context of a social system, or better in the self-description of a social system, it will be viable if it serves its purpose. And its purpose is, following Luhmann, to process meaning and to unify the distinction between actuality and possibility (1984). Gary Marcus introduces the theorem of kluge in the context of researching the mind (2008). Psyches as well as living systems respectively organisms, do not strive for perfection. They strive for viability and any solution that serves that purpose will be evolutionary stabilised. So the focus is on systemic viability and not on truth. This goes as far as understanding that in any given interview that is conducted in a social system, we can allow for blunt lies without any problems for the further cause of research and results (Klein and Weiland 2014).

The focus of systemic inquiry into social systems is sensemaking (Weick 1995) and meaning creation (Luhmann 1984). That relates to a rich tradition in social science and organisational theory. Nevertheless, we need to distinguish between the sharp systemic understanding of meaning as Niklas Luhmann puts it and the sensemaking in organisational theory as for example Carl Weick brings it forward. Luhmann's term is very specific and provides a good understanding of a description of actualities and a description of possibilities. In the medium of meaning a social system processes contingency, options and possible futures which are accessible and can be realised if decided to do so. Weick's sensemaking is less specific. Sensemaking describes programmes and pattern or means which mainly focus on explaining how for example an organisation operates. In that aspect sensemaking describes a rather conservative moment in the evolutionary process of a social system. It describes the blueprints which discriminate and filter behaviour in terms of functional adequacy for the further course of developments. It is the referencing stories and narratives as examples that serves as a blueprint for further activities.

Systemic inquiry can be seen as an interactive sensemaking and meaning creation process. The research default would be the qualitative interview. This will reveal relevant stories, specific semantics and guiding distinctions. For the analysis the single interview may not be so significant. We can assume that like in a hologram the single interview and the stories brought forward there will carry a lot of information about a specific social system, however blurred. The more interviews, the sharper the image becomes. For a multitude of interviews will allow for pattern recognition. There will be foci of attention (Klein 2005). Themes, topics or events around which the stories crystallise. This will give a first impression about the relevance for the social system. And again relevance can be rooted in different areas there may be foci of attention which refer to the identity of a social system and cluster a rather conservative perspective. There may be foci of attention referring to current perturbations or pressing questions or decisions to be made. There may be a balance between references to the past, to the present and to the future. In any case it is important to understand that these stories do not reveal truth but a functional processing of meaning to sustain the social system's viability.

Semantics carry the specifics. The analysis of the stories especially in organisations will reveal specific semantics, phrases and terms which have moved away from their use in everyday language. Very often this indicates sweet spots with a particular sensitivity within the organisational sensemaking. It is worth exploring these sweet spots in terms of the underlying guiding distinctions which by guiding observations create and process what is referred to as reality or the world. Gregory Bateson used to point at those distinction as differences which will make a difference (Simon 1993; Bateson 1979, 1972).

A more specific approach to systemic inquiry is critical narrative inquiry (Jorgensen and Largacha-Martinez 2014). It adds a critical perspective to the straight forward inquiry. By doing so it avoids the conservative self-reference of the organisational sensemaking. The challenge for the research is here the decision about the critical perspective. It introduces criteria into the analysis of story and narratives which are not to be found within the system. It is a way to highlight the system's blind spots in observing and describing itself as a social system, an organisation, a team or a society. It is important to be transparent about the selection process for the critical external perspective and to understand that this eventually adds another layer of sensemaking at the price of creating yet another blind spot on yet another level. In the research practice it has proven to be fruitful to acknowledge the epistemological embedment of the respective critical perspective that was chosen.

This epistemological turn as such can be used to enrich the initial systemic inquiry process as well. This relates to the frame of reference theory which acknowledges that for different sensemaking processes in organisations and for individual stories there is a multitude of paradigmatic references that can be used to cognitively explain a specific action for the individual as well as for an entire organisation (Klein 2013). The most prominent systemic inquiry based research was brought forward in the book Soldiers (Neitzel and Welzer 2011). In the early years of World War II imprisoned German soldiers were systematically overheard and recorded by the Allies to learn more about German war strategies, technologies and weaponry. The recorded conversations however were not so fruitful in that respect. The soldiers were mainly concerned with sensemaking and meaning creation to process and digest their experiences in the war which they tried to explain to each other tapping into a wide array of frames of reference, reaching from Nazi ideology over German history and tradition to religious beliefs and family values. It occurred that the same person was tapping into different frames of references to reason different actions and activities they have been going through. It became very obvious that sensemaking and meaning creation did not follow a homogeneous frame of references, not even a homogeneous pattern but tapped into what occurred as being suitable for the person for the one or the other story.

We are confronted with an ecology of paradigms (Klein 2013) when it comes down to sensemaking and meaning creation in social systems. The term ecology refers to the co-existence of different paradigmatic frames of reference. From ecology that we are confronted with all kinds of possible relationships reaching from confrontational competition via ignorant co-existence to symbiosis (Allen and Hoekstra 1992). An example for the latter may be found in Max Webers's works on the relationship between protestant ethics and capitalism where protestant ethics feed as a value set into work ethics which serve and emphasis capitalism as an economic order and feed back as a re-enforcement into the protestant belief set (1920).

Discourse praxis analysis is a systemic inquiry research setting and follows the praxeological nature of sensemaking and meaning creation in social systems. Discourse praxis analysis acknowledges that the central criteria for sensemaking and meaning creation in social systems is not truth but functional viability. With tongue in cheek it can be referenced to Pierre Bayard's book How to talk about books you haven't read (2007). For a discourse praxis it is of lesser importance what the actual source in a book or document says than what this reference is used for in the actual conversation and discourse. We may be amused to see managers referring to management books they have not read to come up with specific buzz words in their management discourse to describe and reason their very managerial praxis. The amusement will drop dead the very moment we understand that we are looking at the very same pattern in the ranks of the so-called Islamic State when referring to the Qur'an. It may be a different understanding or a misunderstanding or sheer ignorance. The relevant information is not in the book; it is in the discourse practice, and this is what guides the action.

5 Social Systems Research

Systems research is an entirely different approach in research practice. This is to say that systems research takes into account that research as such is a human activity system. All that we said about social systems needs to be taken into account when we look at research. Self-application can be seen as a systemic imperative. Acknowledging the social embedment of any kind of research should be taken for granted when we talk about systems research.

Systems research needs to be a reflexive practice. That quality seems to be the perfect ground for praxeology (Klein et al. 2015). In this regard it can be seen as the end of objectivity in science. Certainly looking at natural phenomena, dealing with physics, chemistry and biology allows to maintain the illusion that the observer or the researcher can be viewed as being distant from the phenomena he or she deals with. In ontological perspective we are not so much challenged. However, from an epistemological point of view any concept of objectivity shall rather be dismissed. For the research into social systems the necessity to acknowledge the systemic embedment is inevitable.

Of course, systems research is as well systematic as it is systemic. To facilitate research and for enhancing feasibility, it is necessary to reduce complexity as well as embracing complexity at the same time. A systematic approach to systems research leads into the classic project management logic. There are conventions to describe the organisational set up of activities which are meant to lead to a specific outcome. It has reason to describe research design in the language of project management. This facilitates the conversation about the research and enables for systemic perspectives on research as a human activity system (Edson and Klein 2016).

A systemic perspective on research leads to an outer and an inner logic. The inner logic refers to the chosen scientific embedment which explains the models, the methods, the instruments and their configuration in the research against an epistemological reflection. A specific set of scientific references predetermines so to speak the round of possibilities of the very research. It enables the researcher to see at a price of creating further blind spots. So any result in that scope needs to acknowledge its previous position and limits. The outer logic refers to social complexity. Any political and cultural aspect of the research needs to be reflected and will reveal itself in a thorough stakeholder analysis. In one university e.g. a certain school of thought will be favoured and discharged in another. Researcher who do not acknowledge this outer logic of their research may find themselves in a position where all of a sudden they seem to work against an entire faculty. The most neglected aspect in that context of systemic embedment of any research is the researcher as a stakeholder himself or herself. Out of the perspective of human activity system the individual is to be found in the external environment of that very human activity system (Luhmann 1984). In consequence, it is necessary for the researcher to reflect and reveal their motivations and world view. The individual is prior to the research and what he or she brings to the table greatly predetermines and limits what later will be referred to as problem structuring and research design (Edson and Klein 2016). In essence, acknowledging the systemic logic of any kind of research should be a prerequisite for any academic endeavour. Up until today systems research is one of the more advanced traditions to acknowledge this.

Research is circular. Although a systematic, project management like approach to research, suggests that research is unfolding on a straight line leading from start to end over time, research is an inevitable learning loop. A well-proven research heuristic is the circular three steps of exploring mapping and trading. The term trading may be surprising here; however, it refers to the image of overseas travel in the seventeenth century. During this century the Netherlands started to build their colonial empire based on long distance overseas trading. Encouraged by a rather liberal and not religiously biased approach to the world, the Dutch created the better maps at the time. It was a more empirical view on the world turning exploration into better mapping, facilitating overseas trade and reducing the risk of overseas travel substantially. When we come back to systems research, exploration feeds into mapping or modelling which feeds into any further activity which are facilitated by the quality of those maps. However, any research activity in the context of social systems research will be recognised by the very social systems and consequently lead to reactions. What the research activities bring may be ignored or rejected; they may also cause changes, rendering the very research data to history. In reference to Paul Watzlawick who explained that we cannot not communicate, we may say research cannot not intervene (Watzlawick et al. 1967). It will inevitably be recognised and processed. And this reaction again can be observed and explored, feeding back into mapping, feeding back into further research activities. It is a learning cycle for the researcher as well as for the involved social system.

Problem structuring and research design lie at the very heart of any organised research (Edson and Klein 2016). Referring to what was said about the systemic aspects of the inner and the outer logic of research we need to acknowledge the systemic embedment of problem structuring as well as research design. Problem structuring is mainly concerned with doing the right research which instantly raises the questions about what is right. The questions cannot be answered without knowing the field, the scientific frame, the methodological frame and the historic description of the field. But equally important we see is that any research endeavour is embedded in a broader stakeholder landscape for which a particular research may be relevant or not at all. In mountaineering it is said that 80 % of all accidents happen on the way from the summit down to the valley, so you better prepare for what comes after the summit. Accordingly, it will be the reception of the research which qualifies for its relevance. Systemically exploring the stakeholder landscape of any research will inform the researcher about the likelihood of acceptance of a specific research, the research question and the way the problem is structured in its scientific and methodological references.

Research design is concerned with doing the research right. On the one hand it has the systematic aspect of research project design. There is a lot to learn about this from project management. Even the distinction between classic project management and agile project management can inform the researcher about what is right to facilitate the research and enhance feasibility. On the other hand, any research design concerned with research in social systems needs to acknowledge that in essence aspects of action research and action learning are inevitable. The very moment a researcher starts to relate to a specific social system, the social system will react on the researcher. Since the researcher is a communicating human being it is more than difficult for the social system to discriminate in an instance whether the research activities can be rejected or need to be processed. Research into a social system will be a disturbance and perturbation of the social system and will cause a reaction. It may be resonance, it may be acceptance, it may be adaptation or it may be rejection of the one or the other kind. Ignorance is not an option.

6 Systems Analytics

Systems analytics are in high demand, not only but certainly with the computational capabilities of the twenty-first century. When we go back to the research heuristic of exploring, mapping and trading we see that mapping is necessarily the most formal part and key for the research's reasoning and communication. If you have a proper map, you can show where you are, where you want to go and what awaits you in-between. This applies for the research process as well as for the social system in focus.

Mapping is a wide field for modelling. We may as well acknowledge that mapping is a sensemaking and meaning creation activity and as such it refers to stories and narratives. Maps serve the purpose of giving orientation to the reader and the audience. Systems analytics, however, open up additional possibilities for the researcher in the twenty-first century. We can think of interactive maps but more so the hope is with dynamic models which map complexity and react on themselves. We know this from causal loop diagrams and the tradition of systems dynamics (Forrester 1968). The idea refers to cybernetics and tries to map feedback loops as the driver of complexity and add the technical capacity to process data leading to dynamic simulations.

If we look at social system research the roots of systems analytics can be traced back to the tradition of operations research (OR) which indeed was mainly concerned with overcoming statistics and stochastics (Keys 1991; Cropper 1989; Ackoff and Sasieni 1968; Churchman 1968; Ackoff 1962; Forrester 1961). Nevertheless, it led to a broad tradition of continuous improvement in total quality management. Of course the early contributions were focussing on industrial production. However, the approach quickly made its way into a management science it was sequentially applied to non-technical systems as well. The suitability of that spread is reflected in the tradition of critical systems thinking (Jackson 1991; Flood and Jackson 1991; Flood and Romm 1996). This already marks the transition from an ontological focus to epistemological considerations. At the same time systems dynamics and systems engineering confronted OR with the inevitability of emergence as a phenomenon which had to be accounted for. Technically, we may refer to that shift as the transition from modelling to simulations.

The digital transformation and big data are about to open up the new chapter of systems analytics. Especially concerned with the developments in social networks drive a new tradition. Currently we cannot overlook where this is leading to. However, we can already reflect and acknowledge that the current approaches especially tapping into big data shift back to an ontological perspective. This has two implications. First we have to acknowledge that the dynamics of digitally enhanced process communication will lead what Dirk Baecker following Niklas Luhmann called the next society (Baecker 2007). If communications are the very element of social systems, we need to acknowledge that computation not only accelerates communication but that by processing communication, for example clicks in a social network and feeding it back into communication, the digital environment substantially interferes with, and we may as well say becomes part of social systems. Hence, for social systems research it becomes inevitable to include systemic simulations which react on themselves providing an additional source of insight, like in the real world.

Modelling politics and culture, in essence social complexity will become the next frontier of systems analytics. From what we know so far, we may suggest that politics can be modelled along interests and culture can be modelled along beliefs. This goes well beyond the early attempts of belief–desire–intention (BDI) software modelling (Bratman 1987) in agent-based modelling (ABM) and multi-agent-systems (MAS) modelling (Salamon 2011; Shoham and Leyton-Brown 2009; Sun 2006; Weiss 1999). At this point in time we may say that scientifically we are not really advanced in this field, however, if we look at the twenty-first century trend of gamification we see that in the games industry especially with strategy games a lot of advances have been undertaken already (Hugos 2012; McGonigal 2012; Werbach 2012; Dignan 2011). We are confronted with an entire generation that is used to integrate simulations of social systems in games like Sim City or Railroad Tycoon, Civilisation, Colonialization, Pirates or the Anno series (1701, 1602, 1503 etc.). In those games this generation, we may call them digital natives, has learnt a lot about systemic interconnectedness and emergent dynamics. The algorithms of these games may be rather trivial and simple as described in the tradition of Eurogames (Burgun 2013; Selinker 2012; Woods 2012), however, it is exactly these assumptions built in simulations which allow for the mapping, modelling and simulation of political and cultural dynamics. It seems to be predictable that this generation will challenge the traditional Enterprise-Resource-Planning (ERP) systems which currently are reduced mainly to accounting, controlling and logistics. This generation will demand more complex modelling and simulation tools which in real time inform them about the implications of managerial decisions not only for the financial bottom line but as well for the well-being of employees and customers. Going back to the human resources (HR) and Total-Quality-Management (TQM) traditions we will likewise see that systems analytics will allow for modelling and simulation organisational and business excellence in an integrated fashion which is lacking at the moment. Although we see a powerful tradition of TQM applications, for example six sigma and lean, we have to acknowledge that in the application they create pockets of excellence in a still not integrated vision of an organisation as a social system. And not only in business but also in politics, governance and administration systems analytics will open new fields providing the conditions for the possibility of public entrepreneurship, social innovations and digitally smart administration. However, it all starts with integrating systems analytics in research and understanding social systems.

7 Systems Savvy

Becoming systems savvy is the challenge of the twenty-first century. Social systems research has been suffering from the success of science. The two aspects that made science advancing at an increasing pace since the enlightenment were objectivity and the reduction of complexity. Applications in technology and engineering seemed to prove the cause. And yet what we may want to acknowledge is that beside an ontological dimension the very aspects of objectivity and complexity reduction created in an epistemological dimension a rather restrictive context in which what we are used to refer to as science could flourish and prove itself. Social systems however, as we saw, are of a different nature. It is subjectivity and complexity which characterise the field. And we may go as far as saying that science and technology can be regarded as a limited special case of human activity systems embedded in social systems. The limitations of this traditional focus of science and technology are revealed by the twenty-first century challenges of which climate change, inequality and poverty are only the more visible peaks of the iceberg. We may want to call for a paradigm shift or better we may want to call for acknowledging the ecology of paradigms we are living in and start to learn reading an epistemological jungle.

We may want to start with systems literacy. And although systems thinking, systems sciences and cybernetics have been around now for a longer while, landmarks of systems thinking as processes of emergence and context dependency are far from being commonplace. Systemicity still seems to be a wide field for exploration, translation and learning. Even for systems research as such the epistemological turn is just about to happen. It has not been earlier than 2014 that the International Federation of Systems Research set up a group to explore systems research out of a systems research perspective (Edson et al. 2016). With a systemic qualification of systems research we now seem to be arriving at a point in time where further advances become possible, especially for social systems research.

Technology as we know from Jim Collins' book Good to Great is never a driver but an accelerator (2001). And although systems analytics builds on a tradition that peaked in the third quarter of the twentieth century, we only now, facilitated by the digital transformation, see a building up momentum. And surprisingly enough it is through the pop culture gamification that ideas of modelling and simulations, politics and culture enter the field.

Social design impact evaluation and social innovation assessment currently enter the institutionalised research agenda. In 2015 for the first time ever, the German Federal Ministry for Education and Research started a major programme to investigate approaches that look deeper into the systemicity of society as a social system. If only the basics of systems literacy would find their way into the self-observation and self-description of governance, administration and management we are bound to see major advances in a very short time, if not to say that break through will be seen in areas so forgotten and conservative that we would never have imagined.

Systemic change is possible. It is bound to sense and meaning. And if we learn to explore the interplay of actualities and possibilities we will learn to draw the maps that will make it possible to lead the course towards next practices and eventually a next society. This is an invitation to research in understanding social systems.

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ForestSim: An Agent-Based Simulation for Bioenergy Sustainability Assessment

Mark Rouleau

Abstract Global development must become more sustainable. To do so, society must adopt a sustainable energy alternative to fossil fuels (Dincer 2000). Second-generation bioenergy from woody biomass (trees and other woody plants) offers a promising alternative that can avoid both the inevitable finite supply problems and climate change impacts of conventional energy (Hoogwijk et al. 2003). However, the sustainability of second-generation bioenergy depends greatly on the availability of a reliable woody biomass supply (Becker et al. 2009). The provisioning of biomass feedstock requires significant land-use land-cover change in the form of forest harvesting activity that greatly impacts local forest ecology, the viability of bioenergy markets, and other socially valued forest uses. These overlapping and often competing interests make estimating the availability of biomass and assessing its sustainability impacts a highly complex task (Berndes et al. 2003). The current chapter provides a framework for using Agent-Based Modeling (ABM) to assess the sustainability of bioenergy production in a way that accounts for this inherent complexity.

1 Introduction

Global development must become more sustainable. To do so, society must adopt a sustainable energy alternative to fossil fuels (Dincer 2000). Second-generation bioenergy from woody biomass (trees and other woody plants) offers a promising alternative that can avoid both the inevitable finite supply problems and climate change impacts of conventional energy (Hoogwijk et al. 2003). However, the sustainability of second-generation bioenergy depends greatly on the availability of a reliable woody biomass supply (Becker et al. 2009). The provisioning of biomass feedstock requires significant land-use land-cover change in the form of forest harvesting activity that greatly impacts local forest ecology, the viability of

M. Rouleau (✉)
Social Sciences Department, Environmental and Energy Policy Program,
Michigan Technological University, Houghton, MI, USA
e-mail: mdroulea@mtu.edu

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bioenergy markets, and other socially valued forest uses. These overlapping and often competing interests make estimating the availability of biomass and assessing its sustainability impacts a highly complex task (Berndes et al. 2003). The current chapter provides a framework for using Agent-Based Modeling (ABM) to assess the sustainability of bioenergy production in a way that accounts for this inherent complexity.

Our chapter begins with a review of current sustainability assessment approaches. We pay particular attention to Life Cycle Analysis (LCA). We explain why conventional LCA limits our assessment capabilities and describe how ABM simulation can be used to complement this approach. Next, we outline the methodology used to develop ForestSim, an ABM simulation of non-industrial private forest owners in the Upper Peninsula (UP) of Michigan, USA. We explain why the UP is a good case study for bioenergy sustainability assessment and then discuss field research we conducted to design ForestSim. Finally, we demonstrate the merits of using ABM simulation for bioenergy sustainability assessment. We pay particular attention to the problem of biomass availability and explain how ForestSim can be used to assess this issue within the broader context of regional sustainability. We believe the following chapter presents a reasonable justification for the use of an ABM enhanced LCA for sustainability assessment purposes and suggest replicating our approach for policy planning purposes in comparable bioenergy systems.

2 Literature Review

It is important to first explain why the sustainability of woody biomass-based bioenergy is worth exploring before demonstrating how ABM simulation can improve bioenergy sustainability assessment. The advantage of bioenergy over conventional energy is that woody biomass is both regenerative (potentially infinite) and the conversion of biomass to energy is relatively carbon neutral (especially when considering replanting; St Clair et al. 2008). The advantage of bioenergy over alternative renewable sources is that bioenergy supplies a steady stream of energy (during both peak and non-peak loads) and it can be used as either a power source (for heating and electricity) or a liquid fuel (for vehicles; Regalbuto 2009). Finally, the advantage of woody biomass-based bioenergy over first-generation bioenergy, such as corn ethanol, is that woody biomass is not a food source and it is unlikely to compete for land with other food crops, which is known to increase food insecurity (Charles et al. 2007).

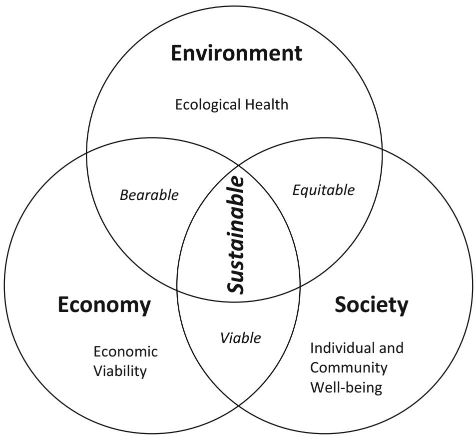
In summary, woody biomass-based bioenergy is more environmentally friendly than conventional energy, it is a more ready substitute for conventional energy than other renewable alternatives, and it is a safer choice for food scarce regions than first-generation bioenergy. Although a mixed renewable portfolio is ultimately preferable, these are the reasons why societies with ready access to forests would want to invest limited community resources in woody biomass-based bioenergy as a starting point to a renewable energy transition. The problem with this approach is that little is currently known about the broader sustainability impacts of woody biomass-based bioenergy beyond the narrow technical advantages mentioned here (Mohr and Raman 2013). We argue that more must be done to explore the sustainability impacts of bioenergy production from a complex systems perspective.

2.1 Bioenergy as a Complex Systems Problem

Two things must be done to properly assess the sustainability of woody biomass-based bioenergy. First, one must establish a definition of sustainability that is assessable. Then, one must select an assessment framework that best fits this definition. The definition of sustainability adopted in this chapter is the widely used Triple Bottom Line (TBL) or three-pillars definition (Hacking and Guthrie 2008). The TBL considers a system sustainable when the processes operating within and across major system components (specifically the environment, society, and the economy) avoid undermining the endurance of any one component over time (see Fig. 1). We have chosen this admittedly broad definition of sustainability because it provides a clear conceptual framework for analysis in that it outlines major focus areas to assess. More importantly, this definition also highlights the critical role component interdependence plays in maintaining sustainable systems.

It is important to note that many researchers remain highly skeptical of the TBL because it relies on an artificial (some claim arbitrary) separation of system components and it can lead to assessments that promote development activities favorable to one component (typically the economy) at the expense of others (Giddings et al. 2002). We argue that much of this criticism has more to do with the inappropriate assessment of TBL sustainability than the definition itself (see Pope et al. 2004). We show below how current assessment approaches inadequately operationalize TBL sustainability resulting in assessments that are counter to what is

Fig. 1 Triple-bottom line sustainability



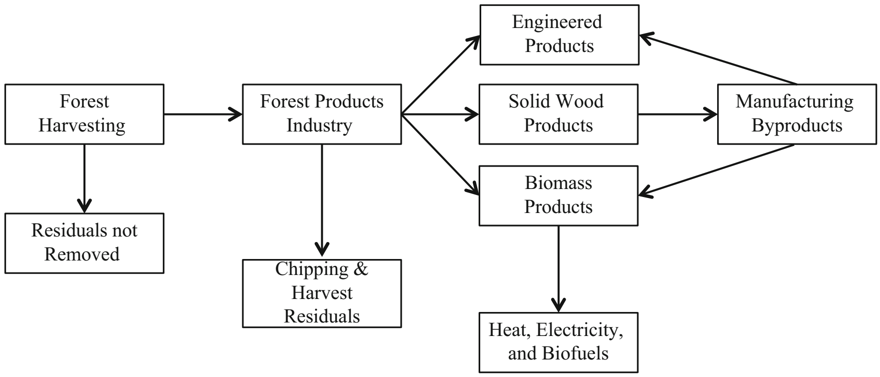


Fig. 2 The full bioenergy production cycle from harvesting to energy

actually conceptualized. Before explaining why this happens, we first describe how to apply the TBL definition to woody biomass-based bioenergy systems so we can see which aspect of TBL sustainability is likely to be improperly operationalized in existing assessment approaches.

A full sustainability assessment should focus on the entire bioenergy production cycle (Becker et al. 2011; see Fig. 2). However, to avoid overcomplicating an already complex problem, we focus specifically on the extraction phase in this chapter. It is here that the value of ABM simulation is most apparent. The extraction phase for woody biomass-based bioenergy centers on the provision of feedstocks to local bioenergy processing facilities. Biomass feedstocks can be obtained from a number of sources including mill wastes, discarded rail ties, forest residues, and whole tree harvesting (D'Amours et al. 2008). Our chapter focuses on whole tree harvesting as a primary woody biomass source. Whole tree harvesting requires significant land-use land cover change to ensure a steady supply of feedstock. Feedstock providers can either dedicate large plots of land to specialized wood crops known to have high energy return values (such as hybrid popular or switch grass) or they can harvest existing natural forests. The energy crop approach typically works best for large-scale operations or for lands with marginal forest value, such as abandoned agricultural lands. Harvesting mixed stands is the method of choice for most small-scale operations with existing natural forests and is most common among non-industrial private forests (Wolde et al. 2016). Once harvesting has occurred, future extraction on a given parcel then depends on the harvesting method (selective thinning or clear-cutting) and the regrowth rate of the forest (Fargione et al. 2008). Nature obviously plays a major role in determining the forest regrowth rate while society often plays a major role in determining the harvesting method (both in terms of economic viability and social acceptability; Lind-Riehl et al. 2015). Thus, at a minimum, we consider a bioenergy system sustainable if it maintains sufficient forest health (environmental endurance), an economically viable biomass market (economic endurance), and socially acceptable forest uses (social endurance). We also want to point out that, even within the narrow scope of the extraction phase outlined here, a high degree of interdependence between humans and the natural system is required to produce woody biomass-based bioenergy sustainably.

The interdependence of humans and nature is a key attribute of bioenergy sustainability and one that ultimately determines the success of a given assessment approach (Pope et al. 2004). To see why this is the case, it is necessary to understand what makes a coupled human and natural system (CHANS) so difficult to assess. CHANS possess numerous features of complexity: non-linear dynamics, self-organized criticality, feedback loops, path dependence, and emergent phenomena (Liu et al. 2007). Many would argue that these properties make CHANS impossible to predict and control (Bonabeau 2002). They further claim that the goal of practitioners should be to simply guide or steer CHANS toward more preferable outcomes (and away from less desirable ones). A better understanding of how complexity creates systemic potential is necessary to accomplish such a "steering" task. This is a very different approach to assessment and problem solving than the traditional approach because it discredits the idea that linear logic can be used to optimize the performance of individual system components to achieve system-wide sustainability. Approaches that treat sustainability like an accounting problem (e.g., aggregating credits and deficits across system components) simply ignore the complexity of CHANS, which results in underspecified models and oversimplified sustainability solutions (Finnveden 2000). Despite this obvious limitation, this is often the standard approach to sustainability assessment today. It is also the reason why we believe TBL is improperly operationalized in most bioenergy assessment efforts as we now demonstrate.

2.2 Current Bioenergy Assessment Tools

The most common approach to sustainability assessment today is Environmental Impact Assessment (EIA) at the project-level or Strategic Environmental Assessment (SEA) at the level of policy, programs, and planning (Pope et al. 2004). Many countries throughout the world legally require developers to conduct EIAs to estimate the potential for significant environmental damage as a result of proposed development activities. EIA estimates are typically based on the "one-off" and unidirectional impacts of individual development projects (Ma et al. 2009). SEAs, on the other hand, attempt to estimate the environmental impacts of existing and future development projects as a whole within the context of a given policy environment. Clearly SEAs are a step in the right direction if the goal is to assess system sustainability. However, SEAs remain quite limited in this respect because they often borrow heavily from static EIA estimation techniques (Pope et al. 2004). EIAs and SEAs both often use some form of Life Cycle Analysis (LCA) to estimate development impacts.

LCA is a popular estimation tool because it encompasses the full spectrum of sustainability impacts (Jolliet et al. 2003), including aspects of development that were often previously overlooked in more narrow impact assessments (e.g., the raw materials extraction or transportation impacts that only indirectly impact the production or use phases of a given product). The disadvantage of LCA is that it uses a simple systems approach (typically equation-based modeling in the form of Cost-Benefit Analysis) to analyze complex system dynamics (Ayres 1995). To simplify the estimation process, LCA must ignore spatially explicit factors (e.g., the spatial distribution of forest cover), actor heterogeneity (e.g., the variance in forest management preferences within a community), social learning (e.g., forest management norms that influence behaviors differently over time), and human–nature feedback loops (e.g., changes in forest cover that impact forest management activates that impact changes in forest cover and so on). This means that the cost-benefit calculations LCAs uses to determine project or policy impacts are often derived from models that only coarsely represent the complex system in question (Matthews and Dyer 2011). Furthermore, LCAs are also quite limited in their ability to estimate non-environmental impacts, such as impacts to the economy or society (Tillman 2000). These limitations greatly diminish the quality of LCA-based sustainability assessment but they also open up new possibilities for an ABM enhanced LCA.

2.3 Agent-Based Simulation for Coupled Human and Natural Systems

Despite the above-mentioned criticisms of LCA, it is not the goal of this chapter to argue that ABM simulation should replace LCA (or Cost-Benefit Analysis). Rather, the goal is to demonstrate how ABM simulation can complement the LCA approach as it is applied to assessing the sustainability of bioenergy production. Prior research in this area has shown that such a fusion of LCA and ABM is both feasible and provides a valuable means to model complexity features conventional LCA tends to overlook (Brown et al. 2016; Gan et al. 2014; Matthews et al. 2007; Davis et al. 2008). ABM is unique in this respect because it models complex dynamics from the bottom-up rather than the top-down like LCA (An 2012). Whereas an LCA models transition states across system components in the aggregate (e.g., X% increase in regional harvesting activity causes Y% loss of regional forest cover), an ABM models the interactions of individual actors and their impact on spatially explicit environmental conditions (e.g., actor A’s harvesting causes parcel A to lose X% forest cover, actor B’s harvesting causes parcel B to lose Y% forest cover, and so on). This attention to individual-level dynamics is what makes it possible for an ABM to replicate, anticipate, and explain emergent phenomena or unexpected system-level patterns that do not follow directly from the logic of individual rules of behavior (Miller and Page 2007). Thus, the major advantage of an ABM enhanced LCA over a conventional LCA is the added value of being able to model a dynamic system with complex emergent properties.

Modeling emergence is critical to sustainability assessment because sustainability itself is an emergent phenomenon (Pope et al. 2004). A sustainable system is clearly more than the sum of its parts because it is not possible to achieve system sustainability by simply maximizing the performance of individual components in isolation of one another. System sustainability is also rarely the end goal of individual development activities because it is not feasible for the scope of most projects to entail the entire system as a whole. This means that sustainability typically emerges (or not) as a consequence of somewhat unintentional feedback across system components. We argue that this idea of sustainability is much closer to the conceptualized version of the TBL than the one that is actually operationalized in most conventional LCA-based assessments. This is why ABM simulation is necessary to ensure a proper operationalization and assessment of sustainability in a complex system (Alfaro et al. 2010).

ABM makes it possible to model the emergent sustainability impacts of bioenergy production in a CHANS. For example, habitat disconnectivity is an instance of an emergent phenomenon that often results from harvesting activities for bioenergy production. It is an emergent phenomenon because no individual forest owner intends to create habitat disconnectivity and habitat disconnectivity often only makes sense at the regional scale not the scale of the individual parcel. Although a conventional LCA could identify hotspots of this type in the form of percent forest cover change for the region as a whole, an ABM enhanced LCA could also identify which specific cluster of parcels is most likely to be responsible for this problem. On top of this improvement in static assessment, ABM also adds a dynamic dimension because it can use static LCA inputs to simulate future dynamics within and across major system components. This makes an ABM enhanced LCA not only statically better but it also adds a dynamic capability sorely lacking in existing LCAs. To see how this works in practice, we now describe the ForestSim ABM simulation used to assess the sustainability of bioenergy production in the UP region of Michigan, USA.

3 Methodology

In the previous section, we laid out the general argument for using ABM simulation to complement LCA sustainability assessment. This section describes how to achieve this goal in practice. The first step is to identify a bioenergy system of interest. We have chosen to model the Upper Peninsula (UP) of Michigan, USA for our bioenergy system. We believe the UP is an important and empirically relevant case study for a number of reasons. First, the UP is a rural and heavily forested region with approximately 90 % forest cover. Second, the UP is economically underdeveloped and faces some of the highest energy costs in the country. Third, the UP's northern latitude and hilly terrain make it a suboptimal location for wind, solar, and even hydroelectric renewable alternatives. These three characteristics make the UP a prime target for woody biomass-based bioenergy.

On top of being a good candidate for bioenergy, the UP also exhibits many features of CHANS complexity outlined above. Much of this has to due with the forest ownership structure that divides UP forestlands into three equal-sized but distinct groups: (1) publically owned state and federal forests, (2) privately owned large-tract forests for timber, and (3) many small-scale non-industrial private forests (NIPFs). It is this third group, NIPF owners, that is expected to provide the greatest share of biomass feedstock. NIPF owners are also much more difficult to regulate because their forest management decisions are highly decentralized and adaptive, their forest management goals are relatively heterogeneous, and their forest use activities are inherently spatially explicit. These are the reasons why we consider the UP an excellent candidate for ABM-based bioenergy sustainability assessment.

With the bioenergy system established, the next step is to develop a qualitative assessment framework. This framework outlines the set of assessable criteria and indicators tracked within the ABM simulation to determine system-wide sustainability. To generate our sustainability scorecard, we used a combination of expert reviews and stakeholder focus groups to develop a community-specific operationalization of sustainability (Vaidya and Mayer in press). The expert review process involved an extensive evaluation of existing sustainability assessment and bioenergy sustainability research. This work resulted in a set of broad sustainability criteria, which mostly conformed to the TBL conceptualization of sustainability, that we used to guide our focus group discussions. We then conducted a series of focus groups with representatives from key stakeholder communities likely to be impacted in each phase of the bioenergy life cycle (see Table 1). The participants of these groups drafted a set of specific and assessable indicators for each of the expert-based sustainability criteria. We then collated the results of our separate focus groups into a single comprehensive sustainability framework. Finally, we conducted another wave of focus groups to discuss, revise, and validate our initial draft framework. The resulting framework (see Table 2) was then used to design the assessment element of the ABM simulation (more on this below).

Table 1 Focus group stakeholder participants

Stakeholder group	Bioenergy role	Participants
Agriculture	Feedstock production; decision-making	3
Forest Owners	Feedstock production; decision-making	12
Tribal Community	Feedstock production; decision-making	2
Timber Industry	Feedstock production; decision-making	4
Venture Capital	Biofuel production; decision-making	4
Forester Consultants	Feedstock production; decision-making	2
Biologist/Ecologist	Decision-making and sustainability	2
State Government	Decision-making and sustainability	11
NGOs	Decision-making and sustainability	3
Bioenergy Users	Bioenergy production/transmission	16

Table 2 Sustainability criteria and indicators from stakeholder focus groups

	Criteria	Indicator
Economy		
	Local development	
		Employment
		Use of local resources
		Infrastructure development
	Energy security	
		Energy dependence
		Competitive cost
	Economic viability	
		Cost of production
		Cost comparison to fossil fuels
		Return over investment
	Resource competition	
		Availability of forest products
		Availability of land for other uses
Environment		
	Air quality	
		Greenhouse gas emissions
		Air pollution
	Ecosystem	
		Biodiversity
		Protection of HCV areas
	Soil quality	
		Productivity/yield
		Soil conservation
	Waste management	
		Residue management and utilization
		Waste management planning
Society		
	Cultural value	
		Access to recreational lands
		Protection of heritage sites
		Access to cultural forest products
		Aesthetics
	Ethical concerns	
		Noise, smell, traffic
		Land rights and open-access
		Work conditions
	Food security	
		Agricultural land-use
		Food and feed prices

After establishing the sustainability assessment framework, the next step is to design and implement the ABM simulation. ForestSim is a Java-based ABM that simulates the harvesting activities of NIPF owners participating in a biomass feedstock market in the UP (this work builds on earlier efforts in Mayer and Rouleau 2013). The simulation takes place within a vector-based Geographic Information System (GIS) using the MASON simulation library. ForestSim uses the National Land Cover GIS layer of current forest cover to represent the agent-environment. This layer determines current cover conditions for model initialization and is updated based on the harvesting activities of the NIPF agents throughout the course of the simulation. NIPF agents are embedded within this environment using a GIS layer obtained from the county tax equalization departments. This layer maps current property boundaries and allows us to assign agents to all existing properties possessing greater than ten forested acres. The database file for this layer also includes critical demographic information that is known to correlate with harvesting proclivity, such as owner income, tax status, residency status (permanent or seasonal), and land tenure. Agents are also assigned an attribute representing their membership status in existing voluntary incentive programs (VIP) based on available membership lists. VIP membership is then used to infer management preferences (different VIPs incentivize owners to achieve different forest management goals) and the likelihood of sharing certain types of management information.

The agent decision-making schema of ForestSim was designed in multiple stages. First, we performed a meta-analysis of existing NIPF owner literature to identify common forest management trends. We then used this information to design an interview protocol to conduct semi-structured telephone interviews with roughly 20 NIPF owners representing broadly different ownership subgroups located in a single county of our study region (Schubert and Mayer 2012). This work helped us to tailor the findings of our meta-analysis to our study region. The data obtained from this study was then used to design an interview protocol for a larger National Science Foundation funded study that conducted face-to-face semi-structured interviews with approximately 40 NIPF owners across all UP counties and an additional 12 interviews with local forest management association leaders (Lind-Riehl et al. 2015). This larger study focused on the role of forest management association outreach efforts, the role of VIP incentivization on enrollment decision-making, and the social origins of NIPF owner forest management preferences. Finally, we used the findings of this qualitative study to develop an NIPF owner forest management survey designed to permit statistical inference to the entire UP NIPF owner population (forthcoming). Logistic regression was used on our survey data to generate individual-level probabilities of adopting alternative management activities based on correlations with key forest owner attributes such as socioeconomic status, residency status, attitudes toward alternative forest management options, perceptions of existing VIP programs, and beliefs about existing social norms regarding forest management. ForestSim agents use this empirically grounded utility function to determine whether to (harvest or not) and how to (select harvest or clear cut) participate in a simulated market for biomass.

A typical simulation run within ForestSim lasts for approximately 100 years with each round representing a single year. Upon activation, agents use the utility function described above to determine their preferred forest management activity for that round. This decision relies on a series of nested probabilities. First, the agent makes a random draw from a normal distribution whose value must exceed the agent's harvest threshold (this is based on the empirically derived logistic regression coefficients for the agent's assigned demographic attributes). When the harvest threshold is met, the agent then makes repeated draws from a normal distribution to determine its set of acceptable harvesting options (selective cut, clear cut with rotation, clear cut without rotation, and so on), starting with the least intrusive option and ending with the most intrusive option for which the random draw exceeds its acceptability threshold. The agent then determines if the current biomass price exceeds the anticipated cost of harvesting and transportation to the processing facility (this cost is estimated based on travel times using current road network data). Finally, the agent chooses the harvest option with the greatest marginal return based on existing tree cover type (to estimate the quality of biomass harvested) and tree stand age (to estimate the quantity of bio-mass harvested). These harvesting decisions are then recorded in a GIS layer and fed through the US Forest Service's Forest Vegetation Simulator to model ecological change in response to the simulated land-use activities of our NIPF agents. This process is then repeated until the simulation is complete.

4 ForestSim for Bioenergy Sustainability Assessment in the UP

The problem of LCA-based sustainability assessment outlined above is one that is being mirrored quite closely in the UP. Bioenergy is an infant industry across the Great Lakes region (this includes the UP but also the entire state of Michigan as well as neighboring Minnesota and Wisconsin) so most assessment efforts take place solely at the project-level, using EIAs to meet the minimum legal requirement for development. The obvious drawback to this approach is that project-level EIAs often overlook the broader sustainability impacts bioenergy can have on the region as a whole. This issue was actually the basis of a recent court case motivating our study in which the environmental group Sierra Club sued the US Department of Energy (DOE) for improperly assessing the sustainability impacts of a proposed bioenergy processing facility in Kinross, Michigan located in the Eastern UP. The court ultimately ruled in favor of the defendant, claiming the DOE had met its procedural obligation in simply conducting an EIA, but Sierra Club was hoping the court would force the DOE to reconsider the validity of its finding of "no significant environmental impact" in light of its narrow assessment approach. For the time being, project-level EIAs will continue to satisfy the legal requirement for bioenergy sustainability assessment but it is obvious that this approach is insufficient to capture the regional sustainability impacts of bioenergy due to its limited scope and lack of attention to synergistic effects across system components as discussed above. The Sierra Club may have lost its legal case but it did highlight an important point about the practical significance of one's sustainability assessment method in the process. The goal of this section is to demonstrate how ForestSim can contribute to resolving this particular methodological problem for bioenergy systems.

To make the case for ForestSim, we compare our ABM approach to a recently conducted bioenergy assessment conducted in our study region from Becker et al. (2009). The advantage of comparing ForestSim to Becker et al. (rather than a project-level EIA) is that this study at least aims to "examine the regional sustainability of forest biomass use" not just identify the "local" sustainability impacts of a specific development project (as in an EIA). Thus, Becker et al.'s broad research goal is closer to the goal of an SEA than an EIA and it also presents a much greater challenge to demonstrate ForestSim's added value. However, it should be noted that the Becker et al. study never really lives up to its own assessment challenge. Rather than "examining regional sustainability" as the study claims, the study actually pursues the much more limited goal of "determining the volume of forest biomass that is sustainably available in the region." Becker et al. assume that answering this availability question is a necessary preliminary step to understanding bioenergy sustainability, which is why their study is titled "An outlook for sustainable forest bioenergy production in the Great Lakes region." Therefore, part of the purpose of reviewing the Becker et al. study is to provide an example of how conventional methods limit one's ability to conduct bioenergy sustainability assessment. The other purpose is to show how ForestSim can be used to accomplish the more interesting assessment goal Becker et al. posed but never actually pursued.

4.1 The Availability of Sustainable Woody Biomass in the UP

First, we briefly summarize the approach and major findings of Becker et al. before discussing opportunities for improvement using ForestSim. Table 3 outlines the study's major findings with a brief note about the method used to devise each. As already mentioned, Becker et al. claim to "examine the regional sustainability of forest biomass use" but they ultimately focus on estimating the "availability of sustainable woody biomass." Sustainable availability in this case is simply a matter of the forest possessing enough biomass to meet demand without exceeding the capacity for regrowth. To determine if this is possible, the study isolates and analyzes a single sustainability indicator that is closely tied to economic viability: the volume of biomass available for harvest. To calculate current biomass availability, Becker et al. first aggregate county-level data on annual integrated harvest volumes under the assumption that the most cost-productive biomass source is residue from ongoing harvest and milling operations for traditional wood products. This volume was found to be significantly less than estimated total growing stock in the region, indicating substantial room for harvest growth.

Table 3 Primary findings of the Becker et al. (2009) study

Sustainability indicator	Assessment method	Assessment finding
The Environment		
Regenerative capacity	Growth stock accounting	Sustainable
Environmental damage	Simulation parameter	Sustainable
The Economy		
Biomass supply	Annual logging residues/simulated thinnings	Sustainable
Biomass demand	Build-out projections	Sustainable
Society		
Ownership	Parcelization trends	Unsustainable
Social acceptance	Public opinion poll	Sustainable
Bioenergy System	Qualitative comparison	Inconclusive

After concluding that the region's forests possess significant volumes of biomass, Becker et al. then construct a biomass supply curve to determine how availability would change in response to increasing harvest and removal costs (the cost of getting biomass to market). To construct this supply curve, Becker et al. used the Fuels Reduction Cost Simulator to estimate the hypothetical costs of harvesting available growing stock. Finally, Becker et al. used data on existing biomass consumers in the thermal heating, electricity, and biofuels industries and proposed development projects in these same sectors to estimate current and projected biomass demand respectively. Their numbers show that projected biomass demand is likely to exceed projected biomass supply, indicating that the existing volume of biomass would be economically viable if harvested. This is how Becker et al. come to the study's main conclusion that there is a sustainable amount of biomass in the region available for bioenergy. However, a closer look at the research design and methodology of Becker et al. shows us why this finding tells us very little about the availability of "sustainable" woody biomass and why ForestSim is necessary to accomplish this goal.

4.2 *Operationalization Issues*

The Becker et al. study is a good example of a conventional assessment approach applied to our study region both in terms of what can and cannot be accomplished. The first thing to note is how their methodology forces Becker et al. to over-simplify the operationalization of the term sustainability. They initially claim to "examine the regional sustainability of forest biomass use" but do so only through the narrow lens of estimating "the availability of sustainable woody biomass." Realizing that their method is unsuitable for assessing sustainability across the major system components of the environment, the economy, and society, Becker et al. decide to simplify this problem even further. To do this, they take an extremely complex phenomenon (sustainability) and distill it into what they believe to be an essential feature: the regenerative capacity of the forest. They then claim that available biomass is sustainable so long as the volume consumed is lower than the volume available for regrowth. On the one hand, avoiding the exhaustion of biomass as a renewable resource is obviously a necessary condition for sustainability but, on the other hand, this is hardly a sufficient condition to declare a bioenergy system sustainable. This is a problem ForestSim can easily avoid because it is possible to operationalize sustainability as a feature that emerges within the ABM environment (more on this below). Thus, from the outset, we can see that the Becker et al. study could have greatly benefited from ForestSim because it would have been possible to assess sustainability directly rather than having to draw conclusions about sustainability based on a less than perfect proxy. In this sense, ForestSim makes it possible to pursue the original research goal (examining the sustainability of regional forest biomass use) rather than a seriously limited version of this goal (estimating the availability of sustainable woody biomass).

The next thing to note is how the Becker et al. approach forces them to compartmentalize the highly integrated concept of sustainability. Becker et al. acknowledge the importance of environmental and social sustainability but most of their actual analysis focuses solely on economic viability. This move is a consequence of the commitment they have made to operationalize sustainability in terms of forest regeneration capacity. Once again, they claim the availability of woody biomass is sustainable so long as existing volume exceeds projected demand plus room for regrowth. Assuming this is all we need to know about sustainability, which we dispute, Becker et al. then devise a series of reasonably sophisticated estimation techniques (described above) to generate the volumes necessary to solve their rather straightforward accounting problem. The obvious error in this logic is that it is impossible to isolate the economics of biomass from the environment and society in which they reside. To address this problem, Becker et al. frequently attach caveats to most of their estimates along the lines of ‘assuming all forested plots are equally responsive to harvesting’ or ‘assuming all forest owners are equally price sensitive.’ These ‘all else considered equal’ caveats are extremely unhelpful when assessing a complex system because it is rarely the case that all else is actually equal in a CHANS. Once again, Becker et al. could have greatly benefited from ForestSim here because it is unnecessary to prioritize the dynamics of one system component over another for the purposes of analytical tractability in an ABM. It is entirely possible to model the feedback among the environment, society, and the economy simultaneously to generate multiple assessment criteria and indicators in the same simulation scenario. This makes it possible for ForestSim to not only replicate Becker et al.’s major findings but also determine the impact of abandoning their ‘all else considered equal’ assumptions.

Becker et al. completely overlook the fact that bioenergy sustainability is a property that emerges from the feedback within and across the economy, the environment, and society. The emergent nature of sustainability makes it unwise to estimate the availability of “sustainable” biomass without considering feedback across system components. Doing so will almost always result in both a serious overestimate of current biomass availability and a static understanding of what it means to be sustainable. Becker et al. do acknowledge this problem and spend a good deal of time discussing the possible impacts of component feedback on their availability estimates without actually incorporating these dynamics into their estimates. For example, in terms of environmental impacts, Becker et al. discuss the critical need for enforceable biomass harvesting guidelines and forest certification schemes to ensure harvesting takes place without negatively impacting soils, biodiversity, or carbon sequestration. In terms of social impacts, Becker et al. discuss the potential advantage of increased job availability in the region but they also add concerns about possible negative impacts to recreation and aesthetics. Most importantly, Becker et al. recognize that their availability estimates completely ignore forest owner willingness to harvest. Therefore, Becker et al.'s estimates clearly overinflate availability unless we assume all forest owners are equally likely to harvest at the going biomass market price. There are countless reasons why this assumption is problematic and all of these reasons are tied in one way or another to bioenergy sustainability. To see why this is the case, we now discuss how to use ForestSim to replicate the Becker et al. study to devise more realistic estimates for the availability of sustainable woody biomass while also examining the sustainability of woody biomass production in the region.

4.3 The ForestSim Approach

The first step to revising the Becker et al. study is to find a better way to incorporate environmental dynamics into the biomass availability equation. This will not only improve the accuracy of the availability estimate but also make it possible to assess the sustainability of environmental change. ForestSim uses the ABM enhanced LCA approach to do this. In the ABM, forest owner agents interact in a spatially explicit representation of the bioenergy system. Each agent is assigned to a specific forest parcel in the landscape and each parcel is assigned a set of ecological attributes to determine the environmental limits and impacts of harvesting activity. This approach ties biomass availability intimately to environmental dynamics because harvesting cannot occur in the simulation if the volume of biomass on an agent's parcel is insufficient, regardless of the agent's willingness to harvest. Three things impact biomass availability on an agent's parcel: the agent's past harvesting activity (which necessitates forest regrowth before the agent can harvest again), soil quality (which impacts the rate and pattern of future regrowth), and the current cover type on neighboring parcels (which also impacts the rate and pattern of future regrowth). Changes in soil quality and neighborhood forest cover are also critical indicators of environmental health that can be tracked throughout the course of the simulation to assess bioenergy sustainability as the system evolves over time. The static outputs of Becker et al. only tell us how much biomass is feasibly available now but it is clear that future availability would be significantly different is everyone with available biomass harvested tomorrow as opposed to rotating harvest activities across the landscape over time. ForestSim makes it possible to assess the full suite of possible and probable harvesting activities.

The second step to revising the Becker et al. study is to find a better way to incorporate social dynamics into the biomass availability equation. Once again, this will both improve the accuracy of the availability estimate and expand the assessment capability into another critical area of sustainability. The best way to introduce social dynamics in ForestSim is through the agent decision-making scheme. We have already highlighted above how the environment limits the agent's harvesting possibilities but this is also true of society as well. The simple cost-benefit analysis inherent in Becker et al.'s supply curve does not capture the social costs that also limit an agent's willingness to harvest: the impacts of harvesting on alternative forest management goals (such as maintaining certain aesthetic features, recreational opportunities, or habitat protection) or the consequences of violating community norms opposed to certain harvesting activities (such as zero tolerance for clear cutting or reluctance to manipulate nature because "nature knows best"). This is why the decision to harvest in ForestSim is based on a set of weighted probabilities derived from responses to a willingness to harvest survey mapped onto actual forest owner demographics. Although it is not feasible to survey every forest owner, if the survey is properly designed, it is possible to infer relationships among owner demographics and harvest probabilities using binary logistic regression. In other words, we use the regression equation to "fill in the blanks" for owners with known demographic characteristics but unknown willingness to harvest values. This makes it possible to model biomass availability using heterogeneous forest owner preferences that better reflect the actual distribution of preferences in the region within a given threshold for error. It also makes it possible to "poll" agents throughout the simulation to determine the degree to which agents can satisfy their non-economic preferences as a means of assessing social sustainability.

The final step to revising the Becker et al. study is to redesign the assessment framework used to evaluate biomass availability and bioenergy sustainability. As it stands now, the quantity of biomass volume is the only assessable indicator in the Becker et al. study. Basically, the system is considered sustainable so long as the volume regenerated is greater than the volume consumed. We have already explained above why ForestSim is a better way to estimate potential biomass volumes in terms of not just economic but also environmental and social constraints. Now we explain how to use ForestSim to track key sustainability indicators. One thing that should be clear from above is that sustainability indicators across all the major system components are already built into the design of ForestSim both at the micro and macro level. In terms of environmental indicators, ForestSim tracks soil quality at the parcel-level and habitat disconnectivity at the landscape-level. In terms of social sustainability, ForestSim tracks owner satisfaction at the agent-level and the distribution of satisfaction at the landscape-level. Finally, in terms of economic sustainability, ForestSim tracks harvesting profits at the agent-level and biomass availability at the landscape-level. ForestSim can then produce time-series reports for these indicators to show changes over time through the course of a simulation as well as a final assessment report that shows the state of sustainability at the end of a simulation run with an indication of the average distribution of variance for each indicator. The resulting assessment report will not only include an estimate of biomass availability that accounts for environmental and willingness to harvest constraints but also a full sustainability analysis on each of the indicators identified above.

5 Conclusion

The goal of this chapter was to explain why ABM simulation is necessary to assess the sustainability of bioenergy production. We began with a review of the advantages of bioenergy over alternative renewable energy sources, particularly for heavily forested regions. We then discussed the limitations of using the conventional LCA approach to assess bioenergy in a complex system. We argued that sustainability was an emergent property of coupled human and natural systems and that ABM was the most appropriate methodology for operationalizing and assessing this phenomenon. We then described the process used to develop the ForestSim sustainability assessment tool using participatory modeling. Finally, we compared ForestSim to a current sustainability assessment study in the UP to demonstrate the merits of the ForestSim approach. The model presented is still a work in progress but we believe the current chapter provides a reasonable justification for developing similar assessment tools for comparable bioenergy systems.

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Toward a Complex Concept of Sustainability

Humberto Mariotti

Abstract The purpose of this chapter is to present some contributions to a complex concept of sustainability. One of the most important is the idea of adding human nature to its variables, since this addition also includes the uncertainty (and hence the complexity) which inherent in all living beings. As for the evidence that human extractivist activities have been harmful to nature and thus to sustainability, Freud's essay "Beyond the pleasure principle", first published in 1920, adds further important elements to the study of the question. The work of the economist Nicholas Georgescu-Roegen is presented as a fundamental contribution to the study of the relations between complexity theory, economics, and the idea of sustainability. The same holds true for the ideas of Gilles Deleuze and Felix Guattari, especially those contained in their book *A thousand plateaus*, with emphasis on their concept of geophilosophy. Finally the complex concept of sustainability is presented. According to it, sustainability emerges from the interactions between ethics, politics and values, on the one hand, and knowledge, technology and science on the other.

1 Introduction

The purpose of this chapter is to relate complexity theory to issues and situations not usually explored when it comes to sustainability. It is well known that approaching a subject from as many as possible number of angles is one of the main methods of complexity thinking. I intend to adopt it here, and for this I will have to resume a few concepts of complexity theory. They will be gradually inserted throughout this chapter, always in regard to their relationships to complexity and sustainability.

Writer and essayist. Independent researcher and author in complexity theory and its aplications.

H. Mariotti, M.D. (✉)
Center for Workplace Diversity Research (CWDR), School of Advanced Studies, University of Phoenix, Phoenix, AZ, USA
e-mail: hmariot@uol.com.br

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I will also turn to a strategy that I have been using for some time with satisfactory results. Its purpose is to introduce complexity into a given event, problem or situation. In my experience, a good way to do this is to insert human nature among the variables of the matter under consideration.

Adding human nature to a problem or situation amounts to adding up uncertainty and therefore complexity. This is easier said than done. In particular this not always should be taken for granted, because the simple fact that we are exploring a given issue by no means guarantees that we are fully understanding it. This is what happens when we are convinced that we are "objectively" exploring a given issue—which is the habitual attitude in our culture. Let us see why.

Our culture has long been fascinated by the idea of objectivity. It well-known that cybernetics has long ago showed that all knowledge is inherently subjective (Lettvin et al. 1959; Goldsmith 1978; Maturana 1980, 1988; von Glasersfeld 1996; von Foerster 2003). Even so, many people in our culture still insist in saying that the world is exactly how we see it. Expressions like "rational" and "objective" have acquired a mantric and fetishist function, given the frequency and emphasis with which they are repeated everywhere and at all times, especially in the media and in the businesses.

That is why it is not easy to insert human nature among the variables of the problems we have to explore. One of the main difficulties is that many people wrongly think that *it is already there*—the same way they are conditioned to think that linear/binary reasoning if the only "correct" way of thinking in our culture.

Accordingly, inserting human nature into a given issue has to be done as a *purposeful, well-thought and very counscious* endeavor to break our natural tendency to see ourselves as "outside observers" in regard to our problems and difficulties. Including human nature provides a kind of realism that we badly need to work on complex issues. That is what the British psychiatrist Theodore Dalrymple once said with other words: "Human motives are rarely pure and never simple" (Dalrymple 2010).

I started using this approach throughout my book *Complexity and Sustainability: what can and what cannot be done* (Mariotti 2013), with results that I consider worthwhile. This chapter includes many elements of this book, to which I will of course add many new considerations.

2 The Complexity of Human Nature

Theories on human nature have proliferated in the history of philosophy. From Machiavelli to Hobbes, from Hume to Rousseau and many others there is a broad spectrum. In his book *The blank slate: the modern denial of human nature*, Steven Pinker (Pinker 2003: 1) discusses some of the most popular of such theories. He sees some of them as the source of many of the problems we face, but as possible sources of solutions as well.

Now let us talk about the need for a theory of human nature, as opposed to the idea that the mind is a blank slate or *tabula rasa*. The idea that the mind is a blank page in which human cultures print their values and beliefs will not be discussed in detail here, as it is an already well studied theme, including by Pinker in his just quoted book. Like him and Edward O. Wilson (Wilson 2004), I also assume that there is a human nature, which in determines what we can actually do.

The British philosopher John Gray, among many other authors, argues that our minds are not impartial observers of the world. They participate in it, and in doing so they build up a vision and a set of attitudes that help us in our journey through life (Gray 2007: 44). It is true that we build our world through our language and interactions; and this leads to the emergence of the so-called conversation networks. Conversely the world also builds us, as we live in constant interaction with it. Thus this process of mutual adaptation does not exempt us to ignore what the world has to say.

If it is correct that our human nature includes a component of self-destructiveness and environmental destructiveness, it may happen that when we try to build up the world we may be actually destroying it. That is what has frequently occurred, especially from the moment we started to develop highly efficient technologies.

We usually declare (sometimes wholeheartedly, but often driven by economic interests) that we want to build a world in which it is possible to live in conditions of mutual respect. Nevertheless our daily experiences show that this is not always the case. We are also built by the world through the ways it can do it—and they are usually determined by the way we treat it. There is much uncertainty in both sides of this co-construction. It is not certain that we can build the world we want, and we cannot be sure that it will respond the way we would like.

There is a set of characteristics of human nature that the experience of centuries and millennia has proved being irremovable. This makes unfeasible many initiatives of prevention and modification of many aspects of human behavior. Even so, to a certain extent humans have shown some ability to protect themselves from their self-destructiveness. Also to some extent, they also have shown some ability to protect the natural environment against their destructiveness.

Common to many deterministic theories is the idea of a sequence at the end of which a “final solution” is reached. The so-called idea of progress resembles the Hegelian march toward the “Spirit”, or Teilhard de Chardin’s journey toward the “Omega Point”. These historicist progressions should be viewed with caution, because the available evidence shows that all too often they are nothing more than sets of well elaborate ideas.

Behind all these proposals is the usual assumption: the idea that the more science and technology the more progress, safety and welfare—that is, the prevalence of the problem-solving mentality. It is obvious that to be true all this would require the adoption of the belief that human nature does not exist.

3 Nature *Versus* Culture

The nature/culture opposition is an important part of the many issues that permeate the human situation. When expressed in terms of Freudian life drives (Eros) *versus* death drives, it means that we humans want to live (that is, we want to stay as far as possible in the organic world). At the same time we want to die (that is, we unconsciously want to get back to the mineral condition). This simultaneity of opposites has long been intriguing and challenging, and so far nothing seems to indicate that the progresses of science and technology will help us to deal with it in an appropriate way.

When we analyze the idea of progress, it is not difficult to realize that it can be seen as a self-deception strategy that has hardly anything to do with material progress in itself. This conclusion comes from many different sources. Sustainability (the good future) is one of them. Medicine (the good care) is another one. Economy (the good trade) is one more. Education (the good upbringing) is still another one. And so on.

The starting point is not that important, since the arrival point seems to be always the same: we live amid a tangle of rationalizations, whose objective is (1) to lessen the challenge of uncertainty, and (2) to lessen the disappointment of knowing that human life has as an important element the need to protect ourselves against our self-destructive drives. In this sense, the much-vaunted Promethean struggle of man against nature in order to dominate it must include people's efforts to control their own unconscious death drives.

Freud describes this fight in his essay Ci*vilization and its discontents* (Freud 2004). On the other hand, it can be said that the sustainability idea is part of a set of the defenses of humans against their self-destructive drives.

Many thinkers have argued that the ability to reflect is intrinsical to human nature and should be included among the basic human rights. Paradoxically this is an area in which man has invested more against himself. For example, it is easy to see that in our current culture everything has been done to curb most of the spaces and opportunities for quiet and reflection. In fact, our current instrumental/utilitarian/quantitative education has contributed much to these efforts.

Spaces for reflection, either individually or in small groups, in general have been almost entirely banned from our schools, workplaces and similar places. Almost everything is done in large scale, hurriedly and amidst much noise. Talks have been replaced by screams, thunderous music and frenetic rhythms. All this makes interpersonal communication, in itself already so hard, something that gradually becomes unfeasible.

4 Beyond the Pleasure Principle

In 1920 Freud published his essay "Beyond the pleasure principle" (Freud 2003a, b: 45–102). In this writing he used the term *Trieb*, meaning "drive" (and not, as often erroneously translated, "instinct"). "Drive" means being driven to a particular object or goal, even if one does not know what it is and without being aware of it. By "pleasure principle", Freud means our tendency to always seek pleasure and avoid pain. From this essay on, he started to admit that there are impulses that go beyond the pleasure principle, that is, some more primitive tendencies that are independent of it.

In spite his Illuminist stance—and therefore his supposed propensity to embrace the idea of progress—, in this essay Freud followed the opposite direction. This became even clearer when he said that for many people it is difficult not to believe in a drive that would tend to lead humans to perfection. This impulse would be the cause of the current achievements of the intellect and ensures our continued development to achieve a kind of superhuman condition. But he was skeptical in that respect: "For my part, I do not believe in such an impulse, and can see no way to keep this pleasant illusion" (Freud 2003a, b: 81).

He previously used to state that human motivation has two fundamental forces: the sexual instincts and the self-preservation instincts. The sexual instinct demanded erotic pleasure, which by alleviating tension at the same time served the spread of species. The self-preservation instinct sought security and growth.

Over time, clinical experience has led Freud to identify what he called compulsion to repeat. This is the propensity of people to bring back to consciousness experiences with no possibility of providing pleasure, and that had never produced satisfaction in the past. These former unpleasant experiences tend to be repeated without producing any kind of contentment. They have emerged among Freud's patients (who at the time included veterans of the First World War) through the compulsion to repeat, a phenomenon manifested in dreams, children's games and other circumstances.

Freud found that this compulsion happened both inside and outside the analytic setting, and suggested that it surpassed the very principle of pleasure. From this point on he developed the concept of death drives, which appears in the above-mentioned essay. He undoubtedly suffered the psychological impact of this discovery, but went on with his research.

As a result, the two above mentioned opposites began to be called "life drives" (Eros) and "death drives", and Freud maintained his dualistic views. According to him the first drives—the most primitive of all—are the death drives, which tend to drive the organic back to the mineral. Agreeing with this view or not, we have to admit that it is an inexorable reality: "To dust you will return".

Freud was not the first one to talk about this matter. In his *Confessions*, St. Augustine (354–430) wrote: "Not everything gets old, but everything dies. So beings are born and strive to exist, but the more they grow the more they haste to not exist. This is their condition" (Saint Augustine, IV, 10). Thus the resistance of so many people to this Freudian conception looks somewhat strange. The American poet T. S. has an interesting verse in this regard: "Human kind cannot bear very much reality" (Eliot 1963: 190).

The resistance aroused by the concept of death drives, even among psychoanalysts of the time as well as among nowadays professionals, was much higher than the observed after the introduction of all other Freudian theories. Freud himself admits that he has dared a lot. He classified his essay as "an extreme line of thought". However, when we observe our human reality it does not look so extreme.

For many authors the concept of death drives is a turning point in Freud's thought. There are those who accept and those who reject it at once; there are authors who see its clinical correlations and those who say that cannot find them.

Anyway my purpose is not to convince the reader to take sides on the importance and usefulness of the death drive theory. The simple observation of daily life shows that we humans are in variable degrees self and hetero-destructive—from person to person and from culture to culture. Whether or not we accept the death drive theory, this is shown by everyday's experience. We do not need Freud's help to realize something that is so evident; but we certainly need his authority to help us to understand this aspect of human nature.

Of course when it comes to human aggressiveness and destructiveness—and to any other controversial question as well—, there will always be arguments and counterarguments of all kinds, origins and trends. We know from experience that our most common behavior is to group the trends in two poles and apply the binary agree-disagree logic to them.

In the case at hand, however, establishing polarities is just a way of evading the issue in itself as well as its implications. This attitude is usually fruitless, because as long as discussions come and go problems accumulate and become even more complex—and the same happens with their consequences. We all know this, yet we continue to deceive ourselves. Moreover, the fact that Freud warned that his considerations could be speculative and provisional has not changed what the daily experience has always shown: human destructiveness has not changed over time.

Even so everything depends on the context. On one side stay Cartesian people, who are supposed to be analytical and "hard" as the sciences that guide them. On the other hand stay "non-Cartesian" people. They are supposedly unorthodox, qualitative, libertarian and soft-minded. Nevertheless this kind of separation only leads to stereotypes. Hanging on to a single pole, whatever it is, only creates orthodoxies, whose main effect is to transform our experiences in fragments that are not representative of the wholeness of the real world.

Despite his initial reservations to the dual theory of instincts, Freud continued to work on it in some further essays that are among his last works. However, he never proposed "certainties" about the death drives, as such an attitude would be inconsistent with his position as a researcher. He rather emphasized the need to keep testing the theory against the continued observation of empirical facts.

It is amazing to notice how many people only see what they want to see, even when they know that ignoring a given phenomenon does not prevent its existence.

That is what John Gray calls “the human innate habit of denying the danger until its impact is imminent” (Gray 2010: 398).

This is not only about denying the danger but also about courting it, that is, inviting it to come and anxiously waiting for its arrival. There seems to be little doubt that this is a manifestation of the death drives. Judging by this and countless other evidences, it is as if people wanted to rush the most their return to the mineral condition. In any case, given the invariable ultimate triumph of death drives, life is only a small oasis in the vastness of the inorganic world. As a doctor, Freud knew that life exists while the anabolic or constructive phase of metabolism predominates over the catabolic or destructive phase.

According to the second law of thermodynamics, life remains as long as the systems are able to delay entropy, that is, the degradation of their internal energy that will take them to the final dissolution. As long as the systems are alive, anabolism and catabolism, despite being antagonistic, are in constant relationship. In this same vein, Eros and death drives are able to live together in a more or less peaceful relationship. However, historical and clinical experience show that along the life process death drives often predominate. It is in these moments that humans become more self and environmentally destructive.

We cannot say that Eros and the death drives are in equilibrium, because this condition does not apply to complex systems, which are in a ceaseless adaptive dynamics. By definition, complex adaptive systems are always far from equilibrium.

From childhood to old age, episodes of cruelty and destructiveness permeate the lives of all of us, both in individual and collective domains. Self-destructive drives are manifested by phenomena such as masochism and suicide, among many others. In this regard, I will recommend the classic work by Karl Menninger *Man against himself* (Menninger 1938). The aggressiveness against others appears, for instance, in sadism, murder and in the wars. In the environmental realm they correspond to the many forms of depredation of natural resources.

According to Freud the real goal of life is death, that is, the return to the mineral realm. Heidegger also sees man as a being-to-death. We have seen already that in several of his essays Freud reaffirmed his belief in human death drives, and noticed that they also turn against the environment. Accordingly, he said that the inclination to aggression is an obstacle to civilization. Eros leads us to life, procreation and the acquisition of personal or cultural training; the death drives drag us to risky and self-destructive behaviors.

It is hard to accept that we are in a self-destructive process, even when this is easily observable. But anyone who has some experience with drug addicts, for example, can easily notice that. All too often people fail to realize the obvious. Even when they notice it, or when it is shown to them, they always try to escape through self-deception or rationalization. It is as if they needed to be coerced to take care of their own health—and as if disease, suffering and finally death constituted a very seductive process; as if they were powerful attractors that could turn health into an undesirable condition.

Freud referred to all that mainly in regard to individuals, but the same applies to environmental destructivity. In this case, it seems that human beings at some point will need to be forced to act on their own favor—as acting against themselves could not require any kind of stimulus. Furthermore, it appears that even if adopted such favorable attitudes would not have much prospects of success.

One question that is always worth to formulate about the consequences of the devastation of the natural environment is why we cannot do, in a major and really significant scale, almost nothing to really prevent or at least mitigate them. It is as if any kind of catastrophic outcome were unthinkable to us.

That said, it is worth analyzing the consistency of the following arguments: (1) our desire, so often proclaimed, to really build a sustainable world; (2) to what extent certain aspects of human nature will allow it to be put into practice as conceived.

The question can be put another way: (1) it is known that over the centuries and millennia humans have shown a tendency to destroy both themselves and their environment; (2) accordingly, the question arises whether or not this behavior—which is the sheer negation of the idea of sustainability—could not ultimately determine our own extinction.

These questions are easier asked than answered. Our culture's dominant Aristotelian logic has led us to believe that: (1) we want to build a sustainable world, which means that what we do or fail to do regarding the environment should not affect our descendants; (2) we already have some technologies to embark on this endeavor; (3) consequently, in theory the only thing we need to do is just to apply them and the positive results will emerge in due course.

But everyone knows that this syllogistic reasoning usually does not work in real life, because its premises (1) and (2) have not been satisfactorily validated by experience. We know that the efforts to solve this problem (that we created ourselves through centuries of predatory extraction) is not an unanimous consensus. For example, there are many people (including the so-called "skeptical environmentalists") who still do not accept that the emissions of CO_2 and other gases from fossil fuels are harmful and responsible for the so-called climate changes.

The second premise is one of many ways of stating the project of modernity and its idea of progress: there is no human problem that cannot be solved through science and technology—and those that have not yet been solved sooner or later will be, because the progress of technoscience is linear and inexorable. But today we know that many of the promises of modernity were not met. If there has been progresses (which is undeniable), in many cases they have been accompanied by human and environmental harmful side effects—which is also undeniable. Even so, the number of people who believe in the idea of progress is still very large.

The British sociologist Anthony Giddens gives an example. He says that the manifestations of global warming are not immediately evident, so most people tend not to do anything about them. They are indifferent to the possibility that some day such changes may acquire such proportions that any initiative to eliminate them will come too late.

That is what he called "the Giddens paradox" (Giddens 2010: 19–21), which can be so described: (1) know that my habits and lifestyle are harmful to the environment (Giddens uses as a metaphor the disseminated use of SUVs, four-wheel traction vehicles that consume lots of fuel); (2) I know that sooner or later the consequences of environmental aggression will turn against me, my family and my neighbors; (3) even so I will not change my consumption style and other habits.

This is a good example of the human tendency to self-destructiveness, as well as to environmental destructiveness. Giddens wonders why people continue to drive their SUVs, that is, why they continue to not include environmental threats in their concerns. He offers some explanations, to which I will add one more: in regard to sustainability, our culture's prevailing quantitative and instrumental worldview does not take into account the human nature, or at most tends to consider it only in a superficial way.

The environment is a complex adaptive system. If we do not understand the theory of complexity we will not understand the sustainability issue in its deepest sense. We will continue to think of it in terms of separate and isolated facts and parts. Or, at most, we will continue to try to understand it only in terms of the market economy, according to which everything can and should be reduced to numbers and business opportunities.

The fundamental argument of this chapter is that in this and in many other contexts it is not always possible to do what we want for the following reasons: (1) we are historically conditioned to think in terms of the Newtonian/Cartesian paradigm (also called "the Socratic method"), which leads us to imagine that good planning is always a guarantee of success in implementation; (2) there are explicit and implicit resistances to our wills and efforts. These include certain features of human nature that lead to self-destructive attitudes which extend to other people and the environment.

Let us state otherwise what has just been said: (1) human nature is complex, because as living beings we are complex adaptive systems; (2) considering the human dimension entails taking into account its complexity; (3) without taking into account human nature and its inherent complexity it is not possible to think realistically about sustainability. Otherwise will be limited to some of its superficial aspects, including the misleading ones as eco-marketing, bureaucratic/ideological ecology, and the ever recurring New Age mystical utopias.

Thus also in this context we need to become aware of the challenge posed by human nature. Even being incomplete, this awareness could help us to realistically assess until what extent we will be able to implement our projects. For that we need a minimum of clarity on two points. First, not all boils down to wanting to do something and then taking action; second, we must realize to what extent we are acting against our own interests, even when we imagine to be favoring them.

5 Uncertainty and Adaptation

In my previous books I have evolved from what I consider, with Edgar Morin, a kind of milestone: the well-known Pascal's sentence "I find it impossible to know the parts without knowing the whole, as well as to know the whole without knowing its separate parts". This fragment has been useful to spell out two of the main characteristics of complexity: first, everything is connected to everything; second, the parts are in the whole and the whole is in the parts.

As important as this Pascal's statement is the notion of coexistence of simultaneously antagonistic and complementary opposites, which means that there are opposites that do not exclude each other and can coexist side by side. These are the paradoxes. Unlike the problems, they cannot be solved and therefore should be managed.

In the 1960s, particularly in Europe, Hegel's thought began to be challenged. In France, Gilles Deleuze (1968: 1) was one of those who took part in this questioning. At the time, he has said that this period was characterized by a "generalized anti-Hegelianism".

The Hegelian idea that contradictions could always be overcome through dialectics began to give way to the need to learn how to work with paradoxes and seek ways to get along with them. This time marks the beginning of a less escapist vision of paradoxes. So far the most common strategy has been trying to deny or undervaluate them at all costs. Dealing with paradoxes is one of the essential tools of complexity thinking, which is also very helpful when it comes to sustainability. In this regard the pioneering ideas came mainly from the works of Stéphane Lupasco (Lupasco 1947).

Uncertainty is an inseparable part of life's complexity. Ralph Stacey, for example (Stacey 2012, pos. 124), suggested calling the sciences of complexity "uncertainty sciences", with which I fully agree. Even when our efforts to reduce uncertainty are seemingly successful, there will always remain a fraction of it that is irremovable, will always be present in varying degrees and will continue to influence our plans and actions. Sometimes it only exists in minimum degrees, but it always has the potential to suddenly increase at any moment. That is what happens in crises. Our triumphs over uncertainty are and will be always partial, which however does not mean that we should stop striving to improve them.

Nevertheless, understanding that it is impossible to eliminate uncertainty altogether is a realistic attitude. Many of our initiatives to reduce error and uncertainty can be grouped under the generic title of "complexity management". Thus doing complexity management means simplifying (reducing in order to understand) what can be simplified, but without yielding to the temptation to oversimplifying (that is, insisting on dealing with complex systems by means of simplistic concepts and processes).

Analytical minded people usually think in terms of immediate causality (one cause, one effect; one effect, one cause). Before the idea of interconnections and nonlinear causality, they feel challenged and tend to fall on defensive attitudes. In their fantasies they fear to be forced to replace their usual way of thinking by other that is antagonistic to it. In other words, many of them do not have the notion of simultaneity and complementarity.

Our culture's difficulty to think beyond the standard linear/binary/analytic pattern (the Socratic method) is undoubtedly the main limitation to the understanding of issues relating to environmental sustainability. In such circumstances, people use to react in the usual terms of "one thing and its opposite". Hence the feeling of loss, insecurity, discomfort, and the consequent resistances. For many people it is difficult to understand that the linear/sequential/binary reasoning that prevails in our culture is not the only one.

We humans are complex adaptive systems that in turn are inseparable parts of the natural world, which is also a complex adaptive system. But we are cultural beings as well. Edgar Morin says that we are “one hundred per cent natural and one hundred per cent cultural”. Accordingly, human thought includes both linearity and nonlinearity. This means that in every set of repetitions is possible to identify some differences and vice-versa.

Complexity thinking shows that we cannot limit our lives to a way of thinking which has not changed for over 2500 years, that is, since Socrates, Plato and Aristotle. Nevertheless this is what happened and still happens—and this is what has been preventing us from understanding the full implications of the idea of sustainability.

Absolute “certainty”, “objectivity” and mechanistic inflexibility only exist in our fantasies and illusions of control. That is what the Socratic/Platonic/Aristotelic thinking pattern (The Socratic method) has been always promising over time. But this promise has been only partially met. Besides, its incompleteness has been increasing over time with our growing perception and understanding of world’s complexity.

Understanding complexity and complex adaptive systems broadens the understanding of the sustainability of these systems. Such phenomenon is a sign of adaptation, which in turn expresses a characteristic of complex systems: the ability to change to live longer and better—which incidentally is another way of defining sustainability.

Sustainability is a natural phenomenon. Sustainability practices are constructs of the human mind. Man is both natural and cultural. These are two conditions that, according to complexity theory, can complement each other although opposite in appearance. Although indispensable, man’s cultural portion in many cases is a hindrance to his natural condition, and also one of the ways through which he exerts his destructiveness in relation to nature.

Thus here is the core the notion of sustainability: to understand whether the natural world will keep being humanly habitable in spite of the presence of the human being; or if it will not follow this way due to human presence.

6 “Certainties” and Human Hubris

What Neil Johnson (2011: pos. 211) calls “the Holy Grail of the science of complexity” is the (in many cases legitimate) will of control that every human being has in varying degrees. In many circumstances the desire to control should be encouraged and supported, provided that it includes the awareness of the constant presence of uncertainty/complexity, which here is equivalent to the recognition of our hubris. In turn, this recognition is the equivalent to the acknowledgement of our limitations.

Glenda Eoyang (Eoyang 2009: 117–118), among many other authors, points out that the heroes of Greek tragedies had a basic limitation (the hubris) that was almost always fatal: they believed that humans could control destiny. “Hubris” has been translated as “excess”, “conceit” or “arrogance”, and ultimately means the desire to control what cannot be controlled and to explain the unexplainable, which nowadays occurs mainly through measurements and simplistic formulas.

Our hubris has been particularly enhanced by science and technology, that is, by the idea of progress. Controlling the uncontrollable and explaining the unexplainable were and still are two ambitions whose practical impossibility is all too often not acknowledged by most people. It is usually only postponed, in the assumption that someday technoscience could provide all the answers.

Chaos theory can be seen as an anti-hubris, that is, a call for realism. It shows that both the world and the living beings are complex adaptive systems. Thus the essence of being alive includes a degree of uncertainty which is not fully reducible to metasurements, rationalizations, determinisms, and ideologies.

In this sense uncertainty is a gift, not a curse. Without it life would be dull and repetitive, a linear path towards mediocrity—which incidentally is how many people imagine and wish it: a succession of simple causalities, false certainties, mechanical sequences, commands to obey, instructions to follow; in short, everything that real life is not.

In our culture, generations of executives have been led to believe that we should not give much value to philosophies and theories. This comes mainly from the well-known American anti-intellectualism, as described by Richard Hofstader in his classic book *Anti-intellectualism in American life* (Hofstader 1963) and in several other studies, which include Susan Jacoby’s work (Jacoby 2008).

Yet is ironic to note that even so our lives continue to be guided by a set of mechanistic and instrumental philosophies—as if life should be seen almost exclusively in terms of numbers, quantities, and immediate results. And, what is worse, by a narrow mindset whose main function seems to prevent us to realize the harm that we have been doing to ourselves by embracing it as the only kind of guidance.

This utilitarian worldview also has made us practically unable to perceive and understand the devastated world that we are going to bequeath to our descendants—to whom we never cease to say that we love and respect.

Our intolerance to error is almost always a manifestation of our intolerance to uncertainty. This in turn is a manifestation of the mindset that has led us to the idea of progress. Our aversion to error stems from the Enlightenment’s assumption that science and technology could enable us to completely eliminate uncertainty or to reduce it to insignificant fractions.

Now let us return to the theses of this chapter. (1) human nature is complex, because as living beings humans are complex adaptive systems; (2) taking into account human nature amounts to taking complexity into account; (3) without this attitude it is very difficult to think realistically about sustainability; (4) if we do not think of sustainability in a realistic way, our “sustainable development” practices will be reduced to a mere set of good intentions.

7 Change, Perception and Resistance

Jared Diamond notes that there is much resistance to the idea that some ancient civilizations have acted in such a way that ultimately contributed to their own decline and disappearance (Diamond 2011: 8). He also notes that the complexity of ecosystems often makes the perception of human-produced disturbances almost impossible to predict, even by professional ecologists.

Actually the main problem is not prediction, but perception. We are poorly prepared to see what happens beyond our immediate surroundings, both in terms of space and time. A good example was the surprise of many people—including some eminent scholars—on the claim that the number of violent deaths has been slowly and progressively decreasing around the world, particularly after end of the Cold War.

This thesis was demonstrated in Steven Pinker's book *The better angels of our nature* (Pinker 2011). He studied human violence since biblical times, and showed how the civilizing process has been promoting its reduction over time. It is a long qualitative study that includes an appreciable quantitative side, as it contains many diagrams, tables and statistical analyses.

Our difficulty to perceive and understand slow and large-scale changes also hinders our perception of how complex is the world we live in. All too often our life practices involve the fragmentation of the world's complexity under the pretext of understanding it (which in many cases is necessary); but they often lead us to oversimplify it, that is, to deny it. This is one of the phenomena that makes us so alienated both from ourselves and from the world.

In the book just mentioned, Diamond points out that the cultures that have collapsed, like the Mayan, lived in periods in which they were among the most advanced of their time. Thus they were far from being stupid or primitive. This may mean that it is possible that the Mayan ecocide was caused by unconscious drives of self-destruction and environmental destruction. These impulses could have been minimal in terms of intensity; but also diversified, multiple, long-acting and therefore extremely difficult to detect.

In the same book, Diamond says he does not know a single case where the collapse of a society could be fully attributed to the harm it has caused to the environment. There is always a multitude of other involved factors, which certainly makes sense when it comes to complexity theory. Nevertheless, in the midst of all this multiplicity and diversity, human nature should have been more taken into account than it usually is. We traditionally prefer to attribute the causes of our problems to external factors, which to some extent is understandable—but not to the extent of abandoning self-criticism.

8 Nicholas Georgescu-Roegen, Sustentainability and Complexity

Nicholas Georgescu-Roegen (1906–1994) was a researcher with an open, multidisciplinary and visionary mind. Born in Romania, his initial training was in mathematics. Then he worked in the USA (Harvard University) with Joseph Schumpeter. This was a crucial period for his later career as an economist, which was especially developed at Vanderbilt University in Tennessee. His most outstanding book is *The entropy law and the economic process* (Georgescu-Roegen 1971).

Georgescu-Roegen was the first to demonstrate the thermodynamic basis of the economy, whose main point can be summarized as follows: in a finite space (the Earth), only can exist a finite amount of usable (low entropy) energy, which inevitably and irreversibly dissipates over time.

He challenged the positions of the Marxist and orthodox economists, according to which the power of technology is unlimited, and therefore will always be able to replace scarce resources and thus increase the productivity of any material or energy source. This optimism, typical of Modernity's idea of progress, is ironically viewed by him: "You cannot imagine a more blunt form of linear thinking" (Georgescu-Roegen 1975).

Here are examples of some observations contained in his works (Georgescu-Roegen (1971, 1975, 1993a, b)).

1. Ultimately, the purpose of the economic process is to transform valuable (low-entropy) natural resources in high-entropy waste. And this will continue, as many of we humans do not realize that what counts in the economy is not a flow of waste materials but an immaterial flow: the pleasure of living.
2. The belief, first described by Stuart Mill, that there can exist a world in which people and resources remain constant is a salvationist ecological myth, posteriorly taken over by Herman E. Daly and others. Their main mistake is do not realize that zero growth cannot exist for too long in a finite environment. Sooner or later this so-called "steady state" would enter into a crisis. So the ideal would be a situation of declining growth. Even in this case, however, entropy would not cease to increase.
3. There is no human technology that could transform energy into matter. Therefore, the accessibility of low-entropy material resources is the crux of the economic process. A piece of coal burned by our ancestors is lost forever. There is no free recycling or industry without waste.
4. Whether or not we exploit the natural resources, energy and matter always will degrade. They will pass from a state of high usefulness (low entropy) to a state of low usefulness (high entropy). Entropy is accelerated by the exploitation of these resources, but the judicious use of appropriate technologies may be helpful to slow down the process.
5. There is no possibility of continuing exponential growth without the discovery of new energy sources. To illustrate this statement, Georgescu-Roegen used a

metaphor. Prometheus inaugurated the Wooden Age: burning wood as a source of energy. The resulting deforestation made Prometheus II necessary: the coal-powered steam engine. The increasing consumption of coal and other reserves of combustible matter has led us to expect the emergence of a Prometheus III Age.

6. Everything seems to indicate that most economists have succumbed to the fetishism of money. There is no cynicism or pessimism in believing that even with nowadays awareness of the entropy issue, mankind could show signs of giving up its present comforts for the benefit of people who will live in the future.
7. Evolution is not a linear repetition, although during short intervals (in terms of evolutionary scale) it can leads us to think otherwise. In terms of survival, mankind presents some peculiar problems. They are not only biological and not only economic problems but bioeconomic problems—hence the need for the creation of a bio-economy.

Gorgescu-Roegen proposed eight points for a minimum bioeconomical program:

(a) All war tools, and not only the war itself, should be prohibited.
(b) Through the use of productive forces and planned, well-intended measures, the underdeveloped nations must be helped to achieve a good life level, though not a luxurious one.
(c) Mankind must gradually reduce its population to a level that can be properly feed only through organic agriculture.
(d) Until the direct use of solar energy becomes a widespread practice and we get to controlled fusion, all energy wastes through overheating, super-cooling, super-lightning, travelling at high speeds, etc., should be regulated and possibly avoided.
(e) We must "cure ourselves" of our attraction for gadgets and ostentatious trinkets. If and when we do this, manufacturers will no longer produce them.
(f) We must get rid of fashion and fads and learn to despise them. Manufactured products should prioritize durability.
(g) Durable goods must be made even more durable by being designed to be repaired.
(h) We must "heal ourselves" of compulsive hurry, and understand that a sufficient leisure time should be allocated and intelligently used.

I suggest that all these items should be confronted with what is known about human nature:

Item (a) implies a substantial decrease of our aggressiveness. The reader could think better of this topic in the light of the studies by thinkers like Machiavelli, Freud, Einstein, Hobbes, Konrad Lorenz and many others.

Item (b) raises the question of whether, even discounting the usual exceptions, our altruism could someday reach such heights.

In the case of item (c), the focus should be on whether our vision is or will be wide enough in terms of space and time.

Item (d) takes us back to our real level of solidarity and altruism.

In items (e), (f) and (g), the reflection should spin around our ability to at least mitigate what Martin Heidegger calls the three forms of alienation of the human being: ide talk (too much talk and too little to say), the greed for news, and ambiguity.

Item (h) raises several questions about our ability to overcome two of our major limitations: immediacy and superficiality.

It is obvious that Georgescu-Roegen never believed that his recommendations could be adopted. He knew that there are exceptions that must be taken into account. On he other hand, he was keenly aware that the vast majority of people would not even think about his proposals. So he closed the above mentioned remarks with a sarcastic statement: "Perhaps, the destiny of man is to have a short, but fiery, exciting and extravagant life . . . . Let other species—the amoebas, for instance—, which have no spiritual ambitions, inherit an earth still bathed in plenty of sunshine".

Of course Georgescu-Roegen's heterodoxy has led him to a head-on collision with the "hard" scientists, as well as with the neoclassical economists, who he called "standard economists". Unsurprisingly enough, these "standard economists" still compose the establishment of nowadays economic thought. They have a predominantly quantitative, utilitarian and mechanistic view of the economic process in which the idea of balance, and the achievement of a "great" or "ideal" state predominates.

It is obvious that Georgescu-Roegen's proposal that the economy should be incorporated to ecology challenged long-established interests and powers. Everyone knows that conventional economics ignores the natural world (though not in its overt discourse), and implicitly supports the misconception that man is separate from nature. Such positions are clearly incompatible with the concepts of complexity, sustainability and complex adaptive systems.

Like Freud and many others, Georgescu-Roegen showed to people what they did not want to see and told them what they did not want to hear. As a result, in due time several maneuvers to isolate and disqualify him started being put into practice. Since 1976, when he consolidated its interest in ecology, he started being ignored by orthodox economists. He was swept under the rug—an attitude commonly seen in some ancient cultures (as well as in not so ancient others), which used to kill the bearers of bad news.

Nowadays Georgescu-Roegen's ideas have been taken up with growing though timid interest. The relationships between economy and entropy are now part of the attention of a reasonable number of heterodox economists. Even so this number is still far from enough to challenge the mainstream economical thought, as well as to arouse the attention of the mainstream scientific community and beyond.

Basically, however, he came to show that life and living beings cannot continue to be beaten by the positivism of the so-called "hard sciences". It is also clear that, on account of his interdisciplinary stance, Georgescu-Roegen should be included in any text that refers to sustainability, complexity and complex adaptive systems.

9 Sustentainability, Complexity, and Human Nature

In a culture like ours, that is becoming increasingly irrational, people constantly demand rationality and "objectivity" from each other. Demands for objectivity are part of an effort to disqualify or cancel subjectivity and diversity. It is the effort of repetition to subdue difference, in which the word "subjective" has come to have an increasingly pejorative connotation.

In spite of the fact that since long ago cybernetics reaffirmed the ancient notion that all perception is intrinsically subjective, the expression "this is very subjective" is still used with pejorative connotations. Nowadays it has a very clear meaning and address. Its target is anything that cannot be standardized, measured and quantified—everything that cannot be easily brought "under control". Along with its explicit oversimplification, it is an indispensable ingredient for any recipe for superficiality, immediacy and low quality disguised as "speed", "consistency" and "objectivity".

Trying to deny or underestimate subjectivity also implies the effort to reduce diversity and risk. Most of those who act that way think that can somehow control uncertainty. In our culture, the efforts to measure and turn everything into numbers has been consolidated as the inductor of the illusion that everything can be controlled. The statement "what cannot be measured cannot be managed" at first seems to be a well-intentioned manifestation of doing the right thing—as it certainly is in many cases. Over time, however, it has became the ultimate expression of the illusion of control.

The relationships between the idea of sustainability and human individualism are often conflicting, but it is also important to understand that not always individualism prevailed in all ages and cultures. John Gray (2010: 157–158) stresses that we should not think that the individualistic way of life is the only road to well-being, and remember several historical lessons, particularly Japan's example. Morin (2011: 86) has the same opinion, and adds that there is no doubt that if selfishness is contagious the same often happens with solidarity.

There is a Gray's sentence that appropriately expresses one of the many facets of sustainability: "If a society is a contract, it is only in Edmund Burke's sense—a contract between the living, the dead and those that are yet unborn" (Gray 2010: 159). On the other hand, he argues that individualism is a historical human destiny: we can mitigate it but not eliminate it.

One good example are the so-called "green capitalists", who in principle agree with everything that is proposed to "save the planet", provided there is no interference with the "business as usual" practices. This argument brings us back to a gap mentioned by John Gray: the distance between the advances in knowledge and technology and those of ethics and politics (with the first ones well ahead). Experience has shown that this gap continues to widen as time goes by.

The "business as usual" argument has two main features. The first one is the simplifying/parochial worldview. The second, born from it, is the idea that our extractivist practices can go on forever without adverse consequences. Everything that refers to a broader worldview and to the preservation of finite natural resources is all too often rationalized, ignored and eventually discarded.

The little or no understanding of the consequences of these attitudes by most people is a worrisome feature. The higher the context in which this phenomenon occur, the lower the collective consciousness of what happens. The most common posture is to expect the appearance of "saviors" (usually "hard scientists", "conventional economists", or both) to solve our problems—which is an obvious variant of the "positive thinking" that in turn underpins the idea of progress.

10 Gaia

The British scientist James Lovelock has become famous for his hypothesis that the Earth—which he called Gaia, the Greek goddess representing the planet—is a complex adaptive system. In due time, the Gaia hypothesis became the target of many resistances, criticisms and questionings, but now it is accepted as a theory by the scientific community. The key to understand Gaia theory is complexity theory, because our planet cannot be studied only through models and computer simulations, although these methods are important and even indispensable parts of the process.

Lovelock criticizes people who did not realize that the evolution of the living beings and their environment are not separate things; it is a process in which everything is connected. Therefore, not only the living organisms or the biosphere itself are evolving; it is the entire system that evolves. This phenomenon has been called coevolution. Lovelock had the invaluable contribution of the microbiologist Lynn Margulis, who added the microbiological view to the Gaia hypothesis, hitherto an approach that saw the Earth as a self-regulated system, but only from the physical and chemical points of view.

According to Lovelock, Gaia includes the *What* and the *Who*. The *What* is the Earth's crust, which is localized between the incandescent center and the surrounding atmosphere. The *Who* is the huge network of living organisms that inhabit the planet and ceaseless interact with it.

Hence the idea of complexity: everything is connected to everything and turns out being a huge mesh. Everything is woven together and evolves together. We should not forget that the term "complexity" comes from the Latin *complexus* (or *plexus*), meaning, "what is woven together".

This network of constant interactions between the *What* and the *Who* is what Lovelock calls Gaia. Currently his main argument is that Gaia is sick and humanity will not survive without a healthy environment: "If we fail to care for the Earth it will certainly take care of itself, which will mean that we humans will no longer be welcome" (Lovelock 2007: pos. 230).

After having developed his first computational model, which he called Daisyworld, Lovelock presented more complex models that confirmed his findings. According to him, human beings are subsystems within a much larger system—

Gaia—, and no matter how hard they try they will not fully control it. This position is contrary to the positivist way of thinking, which suggests that one of the "missions" of man is to fight against nature and dominate it.

Even when all evidences show their status of parts of the natural world, humans continue to insist in being considered separate from it, which is a clear manifestation of the Socratic subject–object separation. This would allegedly justify their position of seeing the Earth as an object, from which they can extract the greatest possible amounts of resources for economic purposes. It is well known that this continued and indiscriminate predatory impetus created many problems for Gaia's self-organization. This view has led to the emergence of concepts such as the principle of responsibility and the precautionary principle.

Hans Jonas (1985), who was inspired by Kant's categorical imperative, created the responsibility principle. According to him, men are defined on the grounds of their responsibility for the benefit of future generations. Nonetheless, if we consider what we know about human nature—particularly after the ideas of thinkers like Machiavelli, Freud, Hobbes, Gray and many others—, we will have a scenario in which Jonas' proposal turns out being a sensible and well-intentioned ideal to be implemented by people who not always are sensible and well-intentioned.

Accordingly, in his essay *The abolition of man* C.S. Lewis (2009: 53–81) discusses the ever-present gap between what is intended and what is possible. He starts by observing that future generations are both "patients and targets" of those who are alive now. In the end, what we call the power of humans over nature is nothing but the power that some men has over others using nature as an instrument. Every generation gets the environment that the previous generation wanted or was able to bequeath to it. As humans tend to rebel against traditions, they also tend to rebel against their legacies. As a result, they insert their own modifications in them.

Also according to Lewis, the alleged progressive control of generations over nature (which is based on the idea of progress) is nothing but the result of power games among men. If it is correct that humans often think and act against themselves, it is also true that we will inherit the fruits of this destructiveness. Accordingly, it is also conceivable that we will bequeath these fruits, (many of them already rotten), to our successors.

If Lewis' arguments are correct, as the generations succeed their power to solve the environmental problems left by their predecessors seem to decline. When we add to this reasoning some of the main aspects of human nature (as I have been doing throughout all this chapter) the inevitable conclusion is that we ourselves are serious obstacles to sustainability.

However, just as we should not have too many illusions, excessive pessimism and cynicism are also unreasonable. If there is a minimum opening to think and act for our benefit we must seize it. But we have already realized that the difficulties are not negligible. Accordingly, Jonas encourages us to act so that the consequences of our actions could not affect those who will live after us.

One of the main Illuminist proposals assures us that knowledge reduces the fear of uncertainty. Thus everything we know—especially what we can measure—would be manageable. However, the idea that the more knowledge and information we have the greater our ability to reduce uncertainty is by no means entirely true. Experience has shown that this is only true to a certain extent, because there are two levels of uncertainty, the epistemological and the ontological.

The epistemological level is affected by knowledge, and uncertainty decreases as it rises. The ontological level—which has inspired the precautionary principle—is relative to the human existence as well as to the uncertainty that is intrinsical to it. Therefore it is not fully reducible through knowledge.

A suitable definition of the precautionary principle is included in the Wingspread Declaration (Goklany 2001: 2): "When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not established scientifically".

In other words: when reality insists on not to adapt to the linearity, the determinism and the simple causality that characterize what we call "scientific" definitions, prudence advises us to make self-protective decisions without taking them into account. This principle acknowledges that not only the linear/deterministic/Newtonian values of the "objective" science should be taken into account in our interactions with the real world.

11 Global Warming

Automotive vehicles and their proliferation are perhaps the most widespread among the many human tools for self-aggression and environmental aggression. At the same time, they are self-deception instruments.

The growing number of cars has made them less and less useful for their originally proposed purposes: being fast, comfortable and safe means of transportation. When we follow the statistics on the number of deaths in traffic accidents, a fact is increasingly striking: the automobile is becoming more and more slow, uncomfortable and dangerous.

Indifferent to all warnings and advices, many people behave as they are deliberately seeking to be exposed to this and other hazards. The awareness that they are acting against their own interests usually does not discourage people to adopt risky habits and behaviors. This once again raises the suspicion that something deeper and impervious to any reasonable arguments is at stake: the death drives.

The resistance that humans tend to develop against measures established by themselves to improve their security is part of these drives. For example, everyone knows that the international conferences on ways to mitigate phenomena as the greenhouse effect and climate changes have lead to decisions whose implementation always face many obstacles, not to mention the minority of scientists who still deny the importance of the anthropic participation in the global warming.

Many advocates of unlimited economic growth (with the support of many political and business leaders) have been helping to create these obstacles. This obviously means that the fundamental principle of self-deception ("what I do not believe is not real and therefore cannot harm me") continues in full force.

Thus one could say that the Earth is increasingly under the attack of its human inhabitants, whether they are aware of it or not (Cave 2014). According to John Gray, there is no possibility of an ecological vision that could free us from ourselves; the improvement of local environments always can (and always have been) be embarrassed by what he calls "rogue countries", ecological terrorism or increasing population. There is always some kind of danger, which in terms of complexity theory means that we are always far from equilibrium—that is, at the edge of chaos. The population issue is one of the most important players of this game.

12 Complexity Thinking as a Philosophy of Difference

It is obvious that climate changes, population growth and the scarcity of food and water are interconnected phenomena. They produce tensions and conflicts from which emerge crowds of refugees, which in turn create problems for the countries to which they are addressed, including varied expressions of racism and xenophobia.

Human migrations are examples of deterritorialization. Along with "territorialization" and "reterritorialization", they are concepts created by French philosophers Gilles Deleuze and Félix Guattari, which, combined with others such as "rhizome" and "assemblage" (*agencement*, in French), allow the analysis and the proposal of solutions to many of the problems related to sustainability. The contribution of these two authors, as well as others like John Protevi, Mark Bonta, Dianne Chisholm and Manuel de Landa, has been invaluable to complement the positions of the British, American, German and Latin schools of complexity thinking, as we shall see below.

The Rio + 20 conference turned out being unable to meet people's expectations as well as the needs of the natural world. In this conclave there was a clear predominance of the interests of the capital over the interests of the living beings. This pattern has been repeated with varying degrees of intensity in several other similar international conferences devoted to environmental issues.

There are always the inevitable "skeptical environmentalists", who from time to time publish books, articles, and give interviews on television and in the Internet, in which they state that the harmful role of humans in these phenomena "is not scientifically proved". Nonetheless, it is well known that there are no more doubts about this matter (*The Economist* 2011). Thus, once again it seems that what more we have to fear are ourselves.

In the mid twentieth century, Hannah Arendt's book *The origins of totalitarianism* arrived to the bookstores. In its last pages she wrote about Kant's suspicion of the existence of a "radical evil", although he has soon rationalized it as a kind of "pervert rancor". But Arendt went further and showed that in the case of totalitarianisms the "radical evil" emerged in a system in which all men have become equally superfluous. Even those who had the power to operate the system (the totalitarian killers, for example) saw themselves as superfluous as everyone else (Arendt 1976: 459).

That is, there was no more space to diversity because standardization and superfluity dulled people's capacity to experience the complexity of life. Thus we should once more bear in mind that the key to understand the concept of sustainability is learning how to deal with this paradox: humans simultaneously strive to live (Eros) and to die (the death drives).

When the story is told this way it seems tragic and dreadful, but we need to think about it in terms of a broader time horizon. If we consider the human scale, death drives sooner or later will triumph in terms of individual lives. However, if we think in terms of a larger scale we will see that individuals die but the species persist. For us individuals this does not make much sense, unless we consider the fact that we are finite, which leads us to value life in terms of quality and quantity and not just in quantitative terms. This is the point in which sustainability finds its best justification; in these circumstances our efforts to slow down entropy always make sense.

The problem centers on the possibilities that we humans (who are characteristically shortsighted both in terms of space and time) could think and act outside the short term, limited spaces and pure individualism. The contributions of technology are mostly operational; they do not reach the point of making us to realize the complexity of the ideas, policies and actions that are necessary to implement them.

In this regard the philosophy of Gilles Deleuze includes important contributions to complexity theory. It is a philosophy of novelty, a philosophy of difference. According to Deleuze the purpose of philosophy is to create concepts. He proposes an ontological foundation whose base is multiplicity, heterogeneity and emergence.

Early in his career, Deleuze was influenced by Spinoza's thought. Other important influencers were the Stoic philosophers, for whom what really counts is the immanent reality. Deleuze's key position is to establish connections, so that new ways of thinking and new ideas will emerge from them. This notion of emergence of new properties is so central to Deleuzian thought as to complexity theory.

The notion of complex causality, as proposed by Deleuze and his associate Félix Guattari, can be summarized as follows: life is desire, and desire is a flow of multiple forces that generate relationships or, to use a Spinoza's expression, to generate encounters. It is a process that involves many vectors and their intersections. Thus it is not possible to think of it in terms of a one-way stream. On the contrary, everything is woven together.

According to Deleuze and Guattari the term "desire" does not mean desire for a thing, a person or a feeling as we generally imagine when we think in terms of subject–object separation. For these authors the desire needs not to have an object, because it is the result of the intersection of the complex flows that characterize life.

Deleuze developed the concept of "nomad sciences", which have the following characteristics: (1) they speak more about flows than about solid structures; (2) they speak more in terms of future and heterogeneity than in terms of the past and stability; (3) they speak about open spaces, where there is often some turbulence; (4) finally, they compose an investigative and questioning method and not just propose theorems. Needless to say, these characteristics could also describe complexity theory and complex thinking.

13 A Thousand Plateaus

The book *A thousand plateaus*, by Deleuze and Guattari, have been considered one of the most important works of the recent history of French philosophy. For the purposes of this chapter, several of the concepts exposed in it—especially assemblage (*agencement* in French), rhizome and territorialization/deterritorialization/reterritorialization—are invaluable. These notions are important for the understanding of complexity theory and its applications to sustainability and its practices.

Deleuze and Guattari have been relatively little cited in connection to sustainability and complexity theory. However, when we try to relate the work of the various complexity schools to sustainability, it is noticeable that just a few of them have the potential that the work of these two authors offers to its study and understanding. This potential has not been recognized as it should be, and I believe that it will still take a while for most people to benefit from all that it can provide. Among other concepts, the book *A thousand plateaus* presents the idea of geophilosophy. It is a philosophy of immanence, whose implications for ecology and sustainability have not been appreciated, as they should be in the pertinent literature.

Sustainability should be thought of in terms of immanence, since it raises the awareness of human responsibility for their predatory actions against nature. This means that something practical should be done about this matter, given the futility of waiting for "transcendental" interventions.

According to Deleuze and Guattari, the world includes a huge set of singularities (their term for the concept of "attractors" from complexity theory) connected through assembling mediators. In Deleuze's metaphor, these connections are loose as the stones of a cementless rustic wall. Both the stones and the connections between them are useful resources for the understanding of complex adaptive systems. The non-rigid connections allow the elements to be at the same time parts of the whole and to preserve their individuality (Deleuze 1993: 110). As it turns out, this is a typical metaphor from complexity thinking.

A thousand Plateaus is in the list of the texts in which complexity, ecology and sustainability are "at home", so to speak. The recognition that it includes an ecological worldview is already a fact, but it is also necessary to recognize in a more extensive way that this book contains an important approach to complexity theory. From now on I will present some Deleuze and Guattari's concepts that are important to the understanding of sustainability and its practices.

14 Assemblage

The definition of assemblage applies to all networks that produce emergent properties, given their ability to bring together heterogeneous materials and forces and intertwining them. Connections and assemblages define complex systems, not vice-versa. A rhizome, for example, is in itself an assemblage. According to Deleuze, assemblage implies connecting and interrelating all elements in both human and non-human realms, however much they seem heterogeneous.

The idea of assemblage should be part of all sustainable development initiatives. I refer here to companies, markets, environmental consulting firms and so on. However, as experience has shown, this only occurs in a minority of them. The idea of connections seen as something practical and operational is still embryonic.

In our culture, most people are not able to see the natural environment as the *physis* described by Deleuze and Guattari in *A thousand plateaus*: the totality of the world and the life it contains, the immeasurable complex network in which everything and everyone are participants. What is missing to most sustainability initiatives is the complex idea of connections, assemblage and belonging. When the idea of connections (which are themselves assembling phenomena) do not exist or is embryonic, the speeches about ecology and sustainability always sound artificial, empty, and faddy.

15 Territorialization, Deterritorialization and Reterritorialization

It has been said that among the three major metanarratives of modernity—Darwin's theory of evolution, Marxism and psychoanalysis—only the first one remains consistent, as Marxism and orthodox psychoanalysis supposedly are in decline. This statement is known as a cause of controversies. Nevertheless, without entering the core of the matter, it is possible to make some considerations about the most likely reasons for all that.

Both Marxism and orthodox psychoanalysis are deterministic, linear narratives. Marxism proposes a progression that starts with class struggles and hopefully ends with the utopian Communism. In psychoanalysis, the phases of the development of sexuality are well known.

The alleged decline of Marxism and orthodox psychoanalysis started to occur when it was realized that everyday experience and many historical facts did not confirmed them, at least not as much as expected. Anyway it is worth to note that the natural environment, with all its complexity, uncertainty and randomness, was not appropriately taken into account both by Marxism and psychoanalysis (less by psychoanalysis than by Marxism).

This fact made Darwin's theory (nowadays complemented by the Neodarwinian approaches) an increasingly current theory. It never failed to consider the fact that the evolution of the species and natural selection are nonlinear phenomena. Darwin's view of the evolutionary process always took into account the earthly environment, where it has always been permeated by uncertainty and randomness. This has made it always congruent with the complexity of the world.

All this is consistent with one of the most important principles of complexity theory: the need to think about things, events and phenomena in their respective contexts and, even more, to think how contexts influence other contexts and are influenced by them. This is what Deleuze calls “sets”. In his *L’Abécédaire* (Deleuze and Parnet 1988), he makes it clear that we never want isolated things: we always want sets. For example, we do not just want a person—we always desire a person in the complexity of his or her context/environment.

Deleuze and Guattari have two important positions in relation to the environment, which occupy much of *A Thousand plateaus* and can be summarized as follows: (1) never fail to contextualize everything in terms of time and space; (2) always consider the multiplicity of actions, feedbacks and interactions that intertwine through triangulations and make networks. That is, we must always bear in mind the rhizome configuration.

These authors propose that every living being has four environments: an interior area (a home or shelter); an outer area; more or less flexible limits or membranes; ecological niches. Let us describe them.

1. The external environment is the natural world that includes the matter and energy required for life. It is the territory of resources.
2. The internal environment (the *milieu intérieur*, as French scientist Claude Bernard has called it). For Deleuze and Guattari this is the territory of “composite substances”. The internal environment is the place of self-regulation of the organisms, that is, the territory of homeostasis.
3. The intermediate realm. This is the area borders or membranes. In the human body, as in almost all other animals, the organs and systems compose a set, but at the same time they are individualized by membranes: the pleura, the peritoneum, the meninges, the fasciae, the synovia of joints and tendons, the layers that make up the walls of tubular organs such as arteries, veins and lymphatic vessels, the myelin sheaths of the nerves, the connective tissue, the immune system itself. All these play approximately the same role. These borders are never completely impermeable. Their selective permeability allows them to promote and regulate the communications between the various organs and systems, which are the basis to the homeostatic process.
4. The fourth space comprises the ecological niches. These are the result of the territorializations that living beings promote to line off their homes (from the Greek *oikos*) or niches, in which they live in interaction with the environment. The ecological niches are ambiences attached or embedded in demarcated territories. They are useful for the study of many issues related to sustainability.

The actions of living beings in their environments always transform them. This phenomenon also changes the environments (this is what has been called “building ecological niches”), sometimes to a degree that can make them impracticable for the life of future generations. In other words, it may rule out most possibilities of sustainability.

The niches are contexts that cannot be thought without the presence of the beings that inhabit them. The species are part of the ecosystems and the ecosystems are part of the species. It is important to consider the ecological niches as houses or addresses, for what is done or fails to be done in them always determines consequences for the sustainability of the systems as a whole.

16 Correspondences and Benefits

According to Deleuze and Guattari the environments are "born from chaos" and are in constant intercommunication. Each one defines itself through an identifier component. The periodic repetition of identifiers characterizes a given environment. The four ambiences above described are coded, that is, each one is defined by a code that is periodically repeated in order to demarcate its boundaries. The codes are not fixed; they are constantly transcoding. This is the way through which an environment relies on another environment or supports it. Or the way through which an environment dissipates and turns into another environment (that is, deterritorialization followed by reterritorialization).

In regard to the *milieu interior* (the homeostatic area) the example of edemas can be mentioned. Edemas are shifts of organic fluids, which normally should be in the veins, arteries, or lymphatic vessels, but that due to increased permeability of their walls, either caused by trauma, inflammation or sluggish circulation, spill over into the connective tissue and thereby come to occupy different ambiences. Edemas can be reabsorbed either spontaneously or as a result of some treatment, that is, they reterritorialize into their original/normal environment.

Similarly the floods or the damming of rivers make the waters to come out of their natural territory and go to different spaces. Human and animal migrations are also examples of the transduction of populations from one environment to another. Predatory human interventions are common causes of deterritorialization, which can often lead to the extinction of some species. As the environments are always open to chaos, their natural complexity can be subjected to such levels of stress that could precipitate critical states.

That said, it is evident that the complex concept of environment refers not only to the space that is outside the living beings. The complexity of reality frequently shows how ineffective are the attempts of "ecological management" and how ephemeral are their results. The so-called "objective vision" of the natural environment and its problems is only conceivable when the observer/manager has the illusion that it is possible to stay out of the system that he or she observes, and manage it through command-and-control practices. Even so some modeling is necessary, provided that models are not confused with reality, as they frequently are.

Every kind of structuring is a form of territorialization. Human societies are forms of territorialization. When they are violated by natural catastrophes, wars and dictatorships, which cause migrations, we can speak of deterritorialization. When a human community recovers the freedom to determine its own destiny we can speak about reterritorialization. Accordingly, territorialization and reterritorization are always exercises of identity.

It is also important to note, as did De Landa (2002), the correspondences between some of the Deleuzian concepts and complexity theory. For example, "singularities" and "black holes" correspond to the attractors, which are forms of self-organization of the matter. "Events" and "lines of flight" correspond to the bifurcations described by Ilya Prigogine.

According to John Protevi, there are four main benefits in complexity thinking: (1) it allows criticizing homomorphism (that is, the assumption that the material world is always chaotic and passive, and thus should be "saved" by laws and divine interventions or by the discoveries of science); (2) it attenuates the reductionism of the natural world by classical physics; (3) it provides a basis for the concept of emergence; (4) it allows the questioning of the idea of top-down causation. From this point of view, Deleuze's works *Difference and repetition* (Deleuze 1968) and *The logic of sense* (Deleuze 1969) are of utmost importance.

17 Geophilosophy

The term "geophilosophy" does not appear in *A thousand plateaus*. Deleuze and Guattari would only use it 10 years later in their book *What is philosophy?* (Deleuze and Guattari 1994: 85). Yet the idea of geophilosophy was already contained in *The anti-Oedipus* and, in more detail, in *A thousand plateaus*. Deleuze and Guattari say that it comes from Nietzsche, who "founded geophilosophy in trying to assess the national character of French, English and German philosophy".

The concept of geophilosophy been studied by several authors, including Mark Bonta and John Protevi (2004: 3). These authors showed that Deleuze and Guattari developed it from the works of Spinoza, Marx, Nietzsche and Bergson, as well as from the complexity theory. The central idea is to show how complex systems can self-organize without commandments from external agents. As already mentioned, the method consists in establishing a new land-based philosophy, that is, a neomaterialist and spatial way of thinking. Along these lines, philosophy could no longer be based on temporality and historicity, and would preferably focus on geography and spatiality.

Bonta and Protevi put it this way: through Deleuze and Guattari's ideas, geography and philosophy turn into a politically and socially informed kind of complexity theory, and produce what in *A thousand plateaus* appears with the name of "The geology of morals" (the title of one of its chapters).

Bonta and Protevi see *A thousand Plateaus* as a facilitator of the philosophy/geography interdisciplinarity. This work includes contributions from a large number of sciences: biology, mathematics, ethology, physics, anthropology and so on. According to Protevi, *A thousand of plateaus* develops is part of a philosophy of difference, with strong political stripes.

Deleuze and Guattari write about systems that are self-organized in its own immanence, that is, that self-organize from within. Thus, as already mentioned, they do not need any kind of interventions and external commands, particularly the transcendental ones. This self-organized kind of network is described through the metaphor of rhizome, which I will describe later on. In a certain sense, geophilosophy evokes Spinoza's statement *Deus sive natura* ("God, that is, the nature").

The Canadian researcher Dianne Chisholm (Chisholm 2007) shows how Deleuze and Guattari rethink some ecological issues “beyond the impasses of the exploitation of natural resources sanctioned by the State”, that is, beyond the extractive “business as usual” postures and practices.

According to her, the book *A thousand plateaus* expresses what Gregory Bateson called “the ecology of mind”. She also points out that Deleuze and Guattari use the term “geophilosophy” as a way to drive their thought away from ideas that supposedly come “from above”, that is, from areas outside the Earthly reality. Like Spinoza’s, their thought is immanent and therefore fully bound to the complexity of the life processes in our planet. Thus, according to Chisholm, the two philosophers propose a kind of thought that maps a non-teleological and unpredictable network of symbiotic interlacements.

Geophilosophy outlines a vision in which the Earth moves through streams and folds. Through this dynamic it stratifies (territorializes) and deterritorializes itself in a ceaseless and creative process. This immanent vision prevents that we idealize science and technology to the detriment of the human condition, that is, it hopefully prevents that we expect from science and technology more than they really can provide. According to Deleuze and Guattari, geophilosophy’s goal is to tune-in with the flows and forces of the Earth, which thus comes to be considered the real issue of philosophy.

The idea of fluidity and interactivity, which do not lead to imprisoning syntheses, is always present. Geophilosophy takes into account the first principle of ecology: all things come together to form heterogeneous compounds.

Deleuze and Guattari propose an addition to this principle: interconnectivity, multiplicity and diversity join the molar-molecular “double articulation” amid a stream of emotions and intensities. By “molecular” they mean everything that can pulverize, fragment, and disorganize. In terms of the natural and cultural world these are the earthquakes, the tsunamis, the financial/economic crises, the collapses of the stock exchanges and so on.

“Molar” means everything that gathers, everything that constrains, dams and retains: the dams, the channels, the central banks, the World Bank, the leagues, the Davos forum, institutions such as the United Nations and the like. Everything that is fixed and stable tends to territorialize. Everything that is nomadic tends to deterritorialize: the Diasporas, the migrations, and the flows of refugees.

All these phenomena (retrievals, crossovers, territorializations, deterriorializations and reterritorializations) lead to the formation of a huge symbiotic network of matter and energy flows. The visual image thus formed is similar to that of a rhizome: a huge network with no identifiable beginnings or ends. This is what ensures the integrity of living systems over time, that is, the sustainability of all living systems.

This huge rhizome can have its integrity impaired by damages to the environment, and can have it enhanced by a increasing in the number of its interconnections. In other words, anything that reduces the connectivity between the elements of a system also decreases its complexity and thus its adaptability. Everything that preserves or enhances the connectivity between the elements of a system also increases its adaptability and therefore its sustainability.

Geophilosophy is by no means limited to the quantifying and analytical aspects of the ecosystems. On the contrary, it states that all attempts to imprison the ecology into restrictive models limit the understanding of its complexity. When this happens, things come to be seen more in terms of "how it works" (as seen by an outside observer) than in terms of "how it is" (as experienced by a participant observer).

18 Rhizomes, Forests, and Water

Deleuze and Guattari originally presented the concept of rhizome in a separate booklet, which later became the first chapter of *A thousand plateaus*. These two authors created it as a way to metaphorize the networks, which are typical of complex adaptive systems. When a particular point of a given network becomes more visible, this does not mean that the rest of the system is idle. Rather, the rest of the system is the foundation that supports the point that stands out at a given moment.

The concept of rhizome also refers to a specific mode of thinking. Deleuze and Guattari explain the difference between the "rhizome" and the "tree structure". Trees are unidirectional and linear (roots, stem, branches, leaves, and fruits). Rhizomes are multidirectional. They are fasciculate structures, so any of their points are in either immediate or immediate connection with all the others.

In *A thousand plateaus* there are many examples of rhizomes: rivers, social gossips, the unconscious, the ants and many other social insects, fungi, tropical forests, terrorist forces that maintain global cells (of very difficult or impossible elimination, given their decentralization), and so on.

At this point it is interesting to outline the main points of the concept of rhizome, which Deleuze and Guattari present in the first chapter of *A thousand plateaus.*

1 and 2. Principles of connection and heterogeneity. The rhizome is not linear. It is multidirectional and in its structure everything is interconnected. There is no center or fixed points of entry and exit. An isolated tree is a linear structure, but when together (as in the forests), the trees make up large rhizomes, so one should not imagine that rhizomes are always the opposite of the isolated trees. Hence Deleuze and Guattari's advice: "Kill the trees (which represent the linear way of thinking) in your head and pave the way for the concept of forest, that represents rhizomatic complexity".

3. Principle of multiplicity. According to Deleuze and Guattari, only when multiplicity is seen as a noun it ceases to be related to the unity. All multiplicities connect with other multiplicities and in doing so they deterritorialize and are no longer focused and limited.
4. Principle of asignifying rupture. A rhizome can be sectioned at a given point, but it will regenerate in one of his previous lines or even in

others that may arise. As an example Deleuze and Guattari say that it is impossible to exterminate the ants because as a whole they make up a big animal rhizome, which can regenerate even after almost complete destruction. In other words, rhizomes are complex adaptive systems. The rhizome principle can be applied to many other phenomena. The development of malignant tumors is an example, which points to the limitations of exclusively local treatments.

We have already seen that when viewed in isolation trees have not a rhizomatic configuration. However, when considered in their interactions with the environment they show rhizomatic settings, because they are in connection with the air, the rain, the wind and other trees. The same goes for the animals (the ants and many others), the humans beings and their societies.

5 and 6. Principle of cartography and decalcomania. Based on the above principles, it is not difficult to infer that rhizomes are not subordinated to structural and generative models. Rhizomes are maps, not routes. In this regard Deleuze and Guattari use a metaphor from Proust's classic *À la recherche du temps perdu* (Proust 1999: 1210), and argue that an orchid is not limited to reproduce the route of a wasp. Their relationship is dialogic: the insect and the flower it attends comprise a rhizome. Here lies the difference between a map and a route.

The map sets an experimental relationship, which is part of the real world. This kind of relationship is open, accessible and always ready to change according to the new connections provided by its opening and accessibility.

Deleuze and Guattari emphasize that due to their complexity rhizomes have multiple entry points. On the other hand, routes are schematic, predictable and tend to get back to the same point. Until we are able to think also in terms of rhizomes we will be "arboreal individuals" and, according to another well-known metaphor, the trees will not allow us to see the forest.

The concept of geophilosophy has been detailed in various ways by several authors. Accordingly it has reached a level of detail that cannot be brought to this chapter. Anyway it remains important to bear in mind that the sustainability issue must not be examined and understood only from the utilitarian perspective, but from economical, political, social, and many other angles as well. In all cases human nature should be inserted among the variables.

Adopting the utilitarian perspective as the only one amounts to culturalize the complexity of the environment, which is a rudimentary way of dealing with it. Some degree of culturalization is undoubtedly necessary for management purposes, but we are not just managers: we are above all human beings, and systematically denying our condition is a form of self-destructiveness.

We already know that forests are large rhizomes. But homogeneous, symmetrical and silent plantations, which do not harbor or harbor very few birds, insects and other animals, are just sets of trees not truly connected to each other. They are just arrangements, modeled by a sequence of mechanistic actions. Their complexity is lost and the same can be said of their adaptability. As a result they are high entropy arrangements. A symmetrical, artificially made plantation, set from outside by managers, is not able to self-organize unless it is left to its own. In such a case, rediversification and self-organization will take a long time to happen.

Silent and poorly diversified forests are not true rhizomes, because their level of complexity is almost none. Their artificial symmetry constrains their natural diversity. Such systems may be useful in terms of economic interests, but not so good in terms of biological interests. Their economic function is only justified to the extent that appropriate steps have been taken to ensure that their environmental impact is as much as possible reduced. Nevertheless, for all we know so far such steps have been more rhetorical than real.

Symmetric forests are products of the mathematization that humans impose on the natural world. They are industrial artifacts that reduce the complexity of the biome to the over-simplification of timber-producing systems. It is like reducing the soil to the types and quantities of minerals it contains.

Until the notion of rhizome complements the isolated tree model, we will not be able to see a forest as it should be seen and understood. We will continue to see separate trees or at most the forest as a linear sum of trees. As long as this posture is unchanged, most of the forests probably will continue to be devastated. On the other hand, authors like Protevi and Bonta have been doing creative experiments with the concept of rhizome, with the aim of improving the ecological literacy of people.

All these considerations also apply to water. According to Protevi, what we call "water" is not only a compound of two atoms of hydrogen and one of oxygen. Water is a hydro-bio-litho-political complexity. Protevi outlines a geohistory of water, which challenges the dominant molar model of hydraulic management, as exemplified by the damming of rivers in the American West. A realistic history of water should include a plurality of micro-networks of nature and culture, as well as the movements of deterritorialization and reterritorialization of many nomadic and sedentary forces.

The rivers, for example, should not be seen as mere flows of water that run between their margins. Their multiple interactions with the environments of which they are part show that everything participate in them and vice-versa. Their waters contain fragments from the land they cross and its composition changes as they flow and receive tributaries, incorporate new mineral and organic materials, and so forth. Therefore, as Deleuze and Guattari say, rivers are also rhizomes.

19 The Complexity of Sustainability

Sustainability initiatives in which prevails the so-called "business argument" do not take into account the human dimension. This omission is the result of the subject–object separation, which in turn is a characteristic of the Socratic way of thinking. Neoclassical economics, which sees both the economic process and the living beings as separate from nature, follows the same path. That is why human nature must be included in all sustainability studies and practices. Nevertheless, such inclusion should not be done uncritically, as if human beings were perfect and therefore always able to do what they want the way they want.

In predatory terms, human beings not solely compete with their peers: they are in a ceaseless competition with everything that exists in the natural world. The examples are legion and include indiscriminate hunting and fishing, uncontrolled deforestation, the burning of forests to produce charcoal and make room for monocultures, and so on. These phenomena can be traced back to some of the fundamental traits of human nature, particularly immediatism, self-centeredness and destructiveness.

Effective sustainability practices require an approach that could complement our dominant Cartesian/Newtonian paradigm, without however discarding it. For that we would need to change the dominant thinking pattern of our culture.

Therein lies the great difficulty, which in practical terms amounts to how to free us from our conditioning by binary logic. In the case of the so-called sustainable development, for example, we are faced with paradoxes at every step. In this context, as in most others in the real world, we have to acknowledge that there exist more paradoxes than problems, whether we like it or not. In other words, there are more nonlinearities than linearities.

A good example is the classic tension between the need to promote economic development and at the same time to preserve the environment. Unless that technicians, economists and politicians quit believing that issues like this are *always* problems to be solved (when in fact they often are paradoxes to be managed), nothing really effective will be done in this regard.

Non-human living systems do not compete with each other in a predatory way, and do not prescribe standards of conduct to each other. They determine their behavior according to their own structures, that is, based on the way they interpret the changes and patterns perceived in their environment. Otherwise they would be only obedient to these outside determinations.

Some of the best-known arguments against the idea of man's domination of nature through technology come from Heidegger's essay "The question concerning technology" (Heidegger 1977: 3–35). This work has sometimes been presented as evidence that Heidegger is unconditionally against technique; but in fact his argument denounces the modification of human life by the predominance of the mechanistic mind. In this essay, he draws attention to some points that should be highlighted.

The intensive use of technology has brought undeniable benefits, no doubt; but it has also become a threat to all living beings. Heidegger emphasizes that the same human beings that are under the threat of extinction insist on calling themselves "masters of the planet". By adopting this anthropocentric stance, we are convinced that everything that happens is the result of human actions. As already said, according to Heidegger the main threat comes not only from machines and other manifestations of technology, but from the fact that they have disturbed the very essence of man. John Gray says something similar: "Technical progress leaves only one problem unsolved: the frailty of human nature". Unfortunately that problem is insoluble (Gray 2007: 15).

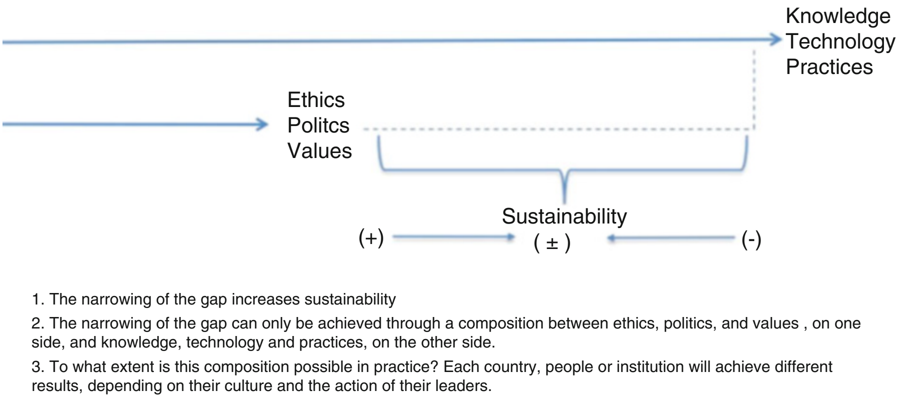

Fig. 1 A complex concept of sustainability

That said, an appropriate definition of sustainability could not be so "accurate" and "clear" as many would like it to be. Sustainability is a complex concept, not reducible to the oversimplification of binary logic: it includes, for example, the ambiguity exemplified by the expression "sustainable development".

Thus a reasonable concept of sustainability stands between two stances: (1) the attitude guided by knowledge and technology, domains in which we are reasonably competent; and (2) the attitude determined by ethics, politics and values. Nevertheless, as noted by Gray in regard to item (2), much of our expertise remain more in the field of intentions and rhetoric than on the area of effective achievements.

As stated before, the idea of sustainability harbors in its bosom paradoxes, oscillations, multiplicities and ambiguities. That is why complex thinking is so helpful to its understanding. Sustainability means not only permanency, but also permanency supported by a network of interlaced environmental elements. All things considered, it is possible to understand that sustainability is at the same time an assemblage and a way to assemble.

At this point we should once again return to Gray's remark: in our culture knowledge and technology (to which I add the practices) are far ahead of ethics and politics (to which I add the values). The gap between these two sets hinders the task of ethics, politics and values, which is to moderate the spurious uses of knowledge, technology and the practices inspired on them. This can be seen in Fig. 1 below:

Figure 1 shows that as long as this gap is as wide as it currently is, this moderation will not happen as expected. Advances in ethics, politics and values tend to increase sustainability and therefore to slow down entropy. Their retreat tends to produce the opposite effect.

On the other hand, a decrease in our fascination by technical knowledge and the resulting indiscriminate use of technologies could also help slowing entropy, with the consequent expansion of sustainability. The most desirable scenario would obviously be an as great as possible approximation between these poles.

That is why it is so difficult to establish a *prêt à porter* definition of sustainability. As a complex concept sustainability will always be fluid, flexible and a constant object of negotiations. Nothing is in equilibrium; everything is in interaction and linked to socio-political disputes.

Pragmatically speaking, it is clear that the last stage of the economic process is the production of waste. Under the laws of thermodynamics, this means turning low-entropy materials in high-entropy rubbish. Thus, as has just been said, everything that slows down entropy and decreases the production of waste tends to increase sustainability. As a result, as already said the narrowing of the above described gap could only be achieved through the possible negotiations between ethics, politics and values on the one hand; and, on the other hand, knowledge, technologies and practices.

This issue cannot be resolved through a simple elimination of one of the poles, because it is not a problem; it is a paradox, and this means that the two poles must get along together.

In the course of this interaction there will always be fluctuations: sometimes one side will predominate, sometimes the other will prevail and so on. But the gap should never be so large that some type of predominance turns out being a dictatorship of one pole over the other, as has been the case in our culture.

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Effects of Policy Decision-Making on Riparian Corridors in a Semi-arid Desert: A Modeling Approach

Aloah Pope and Randy Gimblett

Abstract The resilience of ecologically significant landscapes is often hindered by traditional approaches to natural resource management, which treat ecologic, hydrologic, and social systems as distinct entities. Although acknowledging interdependencies is a great first step in managing complex systems, challenges exist in predicting effects of intervention due to key features such as non-linearity and uncertainty. In order to project the impact of urban populations on riparian corridors in a semi-arid desert, we integrated several modeling approaches to simulate how policy decision-making will effect riparian vegetation along the Upper San Pedro River. Policy decision-making was characterized with a Bayesian Belief Network, allowing uncertainty in the decision-making process to be incorporated. Policy decisions ultimately effected population growth and water use. Urban water demand, calculated by multiplying urban population size with per capita water consumption, was used in conjunction with response functions, developed from MODFLOW, to simulate changes in depth-to-groundwater by well pumping in a spatially-explicit agent-based model. Depth-to-groundwater was then used as an indicator of unique vegetation guilds within the riparian corridor. The model was used to test the effects of policy decision-making on the spatial distribution of riparian vegetation along the Upper San Pedro River. By using the model as a tool, decision-makers may have the ability to make better-informed decisions to ensure the resilience of the Upper San Pedro Watershed.

1 Introduction

In 1973, Holling introduced the world to the concept of resilience, or a way to describe change in ecosystems, using three aspects: ecosystems have the ability to absorb changes in variables and drivers, ecosystems can switch between alternative

A. Pope (✉) • R. Gimblett
School of Natural Resources and the Environment, The University of Arizona, Tucson, AZ, USA
e-mail: aloahpope@email.arizona.edu; gimblett@cals.arizona.edu

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stable states, and ecosystems are dynamic, but ultimately stable, boom and bust systems. Resilience is contemporarily defined as the magnitude of disturbance a system can absorb without changing into an alternate stable state (Gunderson et al. 2010). The installation of management approaches that encourage resilience is adaptive management. Adaptive management involves decision-making under the guise of uncertainty and recommends that new decisions must be made rapidly in light of new information (Pahl-Wostl 2007). Applying adaptive management in the real world is challenging, in part because humans prefer decision consistency and are used to making decisions in stable, predictable systems (Scheffer and Westley 2007; Milly et al. 2008). Additionally, adaptive governance has ambiguous objectives, conditions, and effectiveness (Rijke et al. 2012), and many systems lack an integrated assessment of social and ecologic drivers (Varady et al. 2013).

The concepts of resiliency and adaptation can have varying importance to the decisions of water users. Water decision-makers have already observed that stationarity, or the idea that water systems fluctuate within an unchanging envelope of variability, no longer exists (Milly et al. 2008). Since management systems were designed for predictable systems, water decision-makers will need to apply an adaptive management approach to remain effective. Effective management should include increasing understanding of the feedbacks between the social, hydrological, climatic, and ecological systems, recognizing extreme conditions, and increasing exchange of information with researchers (Scott et al. 2013).

The difficulty in understanding and predicting complex systems, such as semi-arid riparian corridors, is that they possess many interacting parts. Complex systems are difficult to study under traditional research methods because they violate several components of quality research design. Unlike lab studies, complex systems researchers cannot control the environment, isolate key drivers, or replicate the system (Pahl-Wostl et al. 2011). Traditional methodologies generally ignore feedbacks between humans and the environment, nonlinearity, and uncertainty (Walker et al. 2002; Berkes et al. 2003; Fulton et al. 2010). Coupled agent-based modeling, a bottom-up simulation tool, in conjunction with a Bayesian Belief Network (BBN), a statistical model that represents conditional probabilities of factors via a directed acyclic graph, provides a methodology to overcome these challenges. In ABM-BBN modeling, researchers can set the environment and key drivers by representing them as equations, can create replication through repeated model runs, and can incorporate uncertainty by using the Bayesian approach. To test how current policy decision-making could impact riparian ecosystems in the future, we developed a model of urban water demand and its effects on riparian vegetation in the Upper San Pedro River Watershed. Specifically, we look at the impact on riparian vegetation in regards to (1) intensity of change, (2) spatial pattern of change, and (3) likelihood that change would occur.

1.1 *The Upper San Pedro River Watershed*

The San Pedro River is a semi-arid watershed that originates in the Sierre de los Ajos in Mexico then flows northward through agricultural lands until it crosses the border into Arizona, USA (Fig. 1). The river basin is divided into two sub basins, the Upper and Lower basins, based on geomorphology (Tuan 1962). The Upper

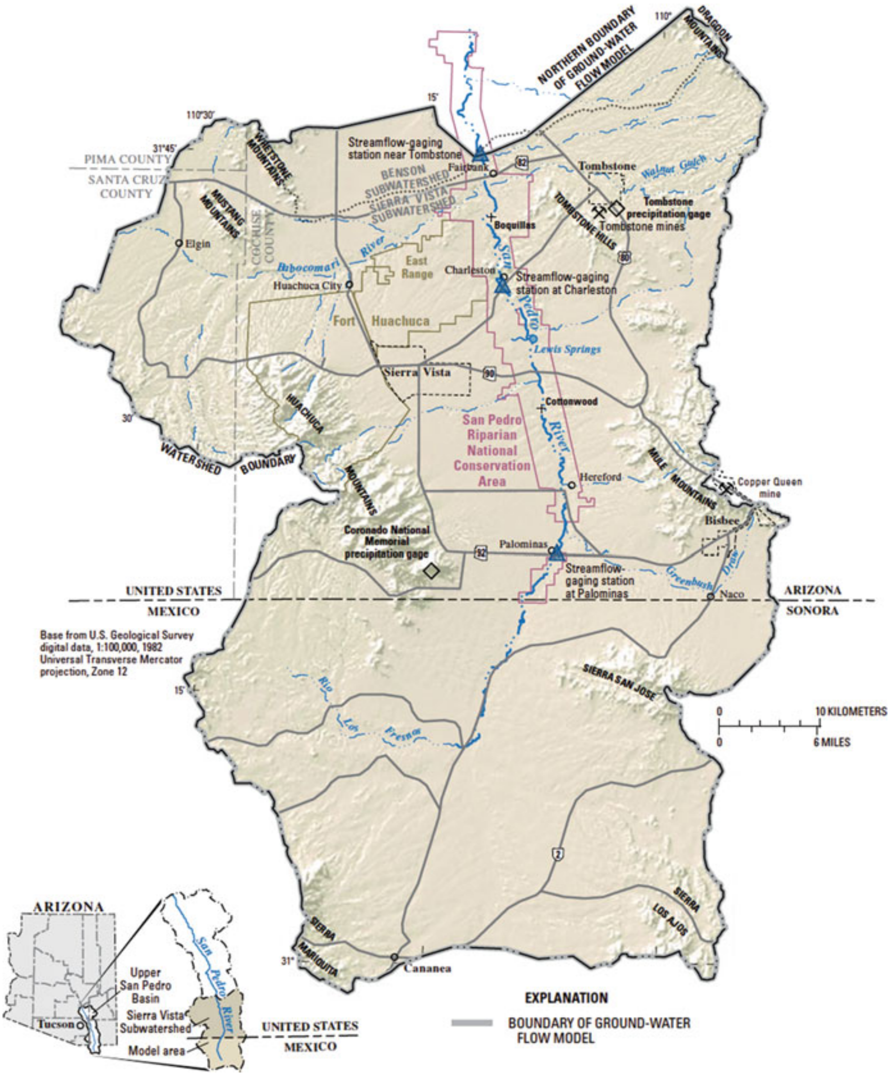

Fig. 1 The spatial extent of groundwater modeling in the Upper San Pedro River Watershed, Arizona, United States and Sonora, Mexico (Pool and Dickinson 2007)

San Pedro River Watershed contains approximately 1875 $mile^2$ and stretches from its headwaters in northern Mexico to a bedrock constriction called “the Narrows”. Mean annual temperature in the Upper San Pedro River Watershed is 17 °C and mean annual precipitation is 360 mm. Precipitation is generally bimodal; short, but intense storms during the summer monsoon (July–September) and long, but less intense storms during the Winter (December–March).

Groundwater can be found in both the permeable alluvium and regional aquifer. Mountain-front recharge, or groundwater movement from higher elevations toward the river, is the main source of recharge for the regional aquifer, while alluvial groundwater is recharged by both precipitation events and groundwater inflow from the regional aquifer. Local groundwater depth is determined by bedrock characteristics and distance to the river/tributaries; however, groundwater pumping has lowered the water table in many areas of the watershed. Historic land use in the San Pedro River Watershed was ranching and farming; however, urban and exurban land use has become more dominant (Dellinger et al. 2006). Water demands from the City of Sierra Vista as well as the largest employer in the region, Fort Huachuca, pose the greatest threats to the Upper San Pedro River riparian corridor (Steinitz et al. 2003).

Although groundwater depths have changed significantly in response to pumping, much of the Upper San Pedro River maintains perennial flow, necessary for maintaining hydric plant species (Grantham 1997). Riparian vegetation in the watershed consists of surface flow-dependent marsh species, a dense canopy of cottonwoods and willows (*Populus fremontii, Salix gooddingii*) near the banks, giant sacaton grasses (*Sporobolus wrightii*) within the floodplain, and woody plants, such as mesquite trees (*Prosopis velutina*), between the grasses and upper bench of the landscape. Ecologically, the riparian corridor hosts approximately two-thirds of avian diversity in America as well as many threatened and endangered species.

2 Agent-Based Modeling

Agent-based models (ABM) are simulations of autonomous entities (agents) that respond heterogeneously to their environment (patches) and have a defined set of simple rules from which to behave. Patches host a set of variables that can be dynamic through time or respond to agent decision-making. Since agent-based modeling is a bottom-up approach, researchers can explore how intricacies in micro-scale behavior can develop emergent phenomena (Schlüter et al. 2012).

The agent-based model consists of three interacting submodels: social, hydrological, and ecological. The social submodel calculates urban water in the City of Sierra Vista, AZ. The hydrological submodel simulates changes in depth to groundwater in response to urban water demand. The ecological model produces unique vegetation communities in response to depth-to-groundwater. The ABM was developed in Netlogo, a multi-agent programmable modeling environment, because it is freely available and user-friendly for non-modelers (http://ccl.northwestern.edu/netlogo/).

2.1 Social Submodel

Urban water demand in the City of Sierra Vista is calculated annually using the equation:

$$\text{Urban Water Demand} = \text{Population} \times \text{Per Capita Water Use},$$

where population size is projected annually and per capita water use = gallons per capita per day.

Population change is simulated with Integrated Climate and Land-Use Scenarios (ICLUS, EPA 2009) for projecting development in the watershed (Bierwagen et al. 2009; Burns et al. 2013). The differentiation between the scenarios fall along two axes: economic vs. environmentally-driven development (A–B) and global vs. regional development (1–2). The different scenarios propose five unique storylines for future growth based on three variables: fertility, domestic migration, and international migration (Table 1). Scenarios A1 and B1 assume low fertility and high international migration, but differ in domestic migration. A2 is the high population growth scenario and assume high fertility and domestic migration. The Baseline scenario is the middle scenario and sets all variables to medium. While B2 also assumes medium fertility, the scenario considers all migration to be low. Projected population growth for the Pacific-south region, including Arizona, was applied for each scenario (Table 2, Bierwagen et al. 2009). Projected population growth was equal for scenarios A1 and B1, while the scenario with the greatest value was A2.

$$\text{A2} > \text{Baseline} > \text{B2} > \text{A1} = \text{B1}$$

Table 1 Summary of qualitative descriptions of each population projection scenario (ICLUS, EPA 2009; Burns et al. 2013)

	Demographic model	
Scenario	Fertility	Domestic migration
Baseline	Medium	Medium
A1	Low	High
B1	Low	Low
A2	High	High
B2	Medium	Low

Table 2 Projected population growth rate for each population projection scenario for two periods of time (ICLUS, EPA 2009; Burns et al. 2013)

	Population growth rate (%)	
Scenario	2005–2030	2030–2060
Baseline	27	20
A1	26	10
B1	26	10
A2	32	32
B2	26	20

The mean (±SD) per capita water use in the City of Sierra Vista from 2004 to 2014 was 144.6 (6.4) and set as the "Current Water Use" scenario (Sierra Vista Department of Public Works 2014). A 20 % reduction in per capita water use was used as the "Reduced Water Use" scenario.

2.2 Hydrological Submodel

Urban water demand calculated in the social submodel is used as input into the hydrological submodel. Although the Upper San Pedro River Watershed originates in northern Mexico, only the Unites State's portion of the watershed was modeled. To simplify the hydrological model, MODFLOW, a finite-difference flow model that simulates flow of groundwater through a 3D delineation of the aquifer, was pre-run so linearized response functions could be used in the model (Fig. 1, Johnson et al. 1998; Pool and Dickinson 2007):

$$s\,(k,n) = \sum_{j=1}^{N_w}\sum_{i=1}^{n}\beta_d\,(k,j,n-1)\,Q\,(j,i)$$

where $s(k, n)$ is the drawdown at observation point k at the end of stress period n, $\beta_d(k, j, n-1)$ is the due to a unit pumping at well j during stress period i, and $Q(j, i)$ is the pumping at well j during stress period i. Response functions were developed for each combination of the 23 high capacity pumping wells that supply municipal water to Sierra Vista and 15 segments of the riparian corridor. The relative pumping capacity of each well was used to calculate its individual allocation of annual urban water demand. Since the response functions are linearized, the agent-based model can simply add the effect of each pumping well for depth-to groundwater.

2.3 Ecological Submodel

Changes in depth-to-groundwater calculated in the hydrological sub-model were used as inputs into the ecological sub-model. The relationships between depth-to-groundwater and riparian vegetation communities were used to predict which community could exist under changing patch conditions. Specifically, marsh vegetation is predicted to be present if surface-water is present, assumed when depth-to-groundwater is less than 2 m. Cottonwood trees are identified when depth-to-groundwater is less than 3 m while *Tamarix,* a non-native species, is predicted when depth-to-groundwater is less than 7 m. If groundwater is greater than 7 m, mesquite is assigned (Lite and Stromberg 2005).

2.4 Initialization of the Model

The Agent-based model was initialized for 2010. Initialization of the model creates the spatial environment for the complex system model. Initial conditions of the spatial distribution of depth-to-groundwater were calculated by subtracting surface elevation by the height of the water table in each 250×250 km cell for 2010 (ESRI 2011). The riparian corridor was defined as a 120 m buffer along the Upper San Pedro River. At the beginning of the simulation, the riparian corridor consisted of 2.69 km^2 of mesquite, 2.18 km^2 of *Tamarix*, 0.91 km^2 of cottonwood and 9.64 km^2 of marsh vegetation communities. Population size of the City of Sierra Vista was set to 43,888 (U.S. Census Bureau 2010), while per capita water use was set to 145 (Sierra Vista Department of Public Works 2014).

Each combination of population growth and water use scenarios was run for 50-years to characterize changes in riparian vegetation communities. At the end of the simulation, the change in area of each type of vegetation community was recorded, as well as the overall percent of the riparian corridor that experienced deterioration.

2.5 Agent-Based Model Results

At the end of the 50-year simulation, the agent-based model predicts that all combinations of population projection and per capita water use scenarios will result in deterioration of the riparian corridor along the Upper San Pedro River Watershed. Within the "Current Water Use" scenario, the population growth scenarios A2 and the Baseline experienced the greatest deterioration, with 5.1 % of the riparian corridor experiencing a change in vegetation community. Scenarios A1, B1, and B2 are only slightly lower, with 4.9 % of the corridor predicted to change. When per capita water use is reduced, the riparian corridor in the A2 population growth scenario is expected to experience the greatest deterioration, with 4.1 % of the corridor changing vegetation communities. The Baseline was the second worst, with 3.8 % of the corridor predicted to change, while scenarios A1, B1, and B2 are the best with 3.7 % of the riparian corridor experiencing change.

If per capita water use remains unchanged, the agent-based model predicts that the area of marsh vegetation will experience the greatest net loss, regardless of different population growth projections (Table 3). Instead, *Tamarix* is expected to increase in area by over 12 %. If per capita water use is reduced, marsh vegetation in the A2 population growth scenario is expected to have the greatest net loss, while *Tamarix* in the A2 scenario is expected to have the greatest gain.

The spatial distribution of deterioration in the riparian corridor is not random. The majority of deterioration occurs in one small stretch of river, near the northern bounds of the hydrological model (Fig. 2).

Table 3 The change in area (km^2) of riparian vegetation communities for each combination of population projection/per capita water use scenarios after a 50-year simulation

	Current GPCD				Reduced GPCD			
	Marsh	Cottonwood	*Tamarix*	Mesquite	Marsh	Cottonwood	*Tamarix*	Mesquite
Baseline	−0.40	0.03	0.28	0.09	−0.28	−0.05	0.28	0.05
	−(4.2 %)	(2.8 %)	(12.9 %)	(3.5 %)	−(2.9 %)	−(5.3 %)	(12.8 %)	(1.9 %)
A1	−0.40	0.04	0.27	0.09	−0.26	−0.04	0.25	0.05
	−(4.2 %)	(4.8 %)	(12.3 %)	(3.4 %)	−(2.7 %)	−(4.4 %)	(11.4 %)	(1.9 %)
A2	−0.40	0.02	0.28	0.11	−0.32	−0.04	0.31	0.05
	−(4.2 %)	(2.4 %)	(12.6 %)	(3.9 %)	−(3.3 %)	−(4.3 %)	(14.0 %)	(1.9 %)
B1	−0.40	0.04	0.27	0.09	−0.26	−0.04	0.25	0.05
	−(4.2 %)	(4.8 %)	(12.3 %)	(3.4 %)	−(2.7 %)	−(4.4 %)	(11.4 %)	(1.9 %)
B2	−0.40	0.04	0.27	0.09	−0.26	−0.05	0.26	0.05
	−(4.2 %)	(4.7 %)	(12.3 %)	(3.4 %)	−(2.7 %)	−(5.7 %)	(12.1 %)	(1.9 %)

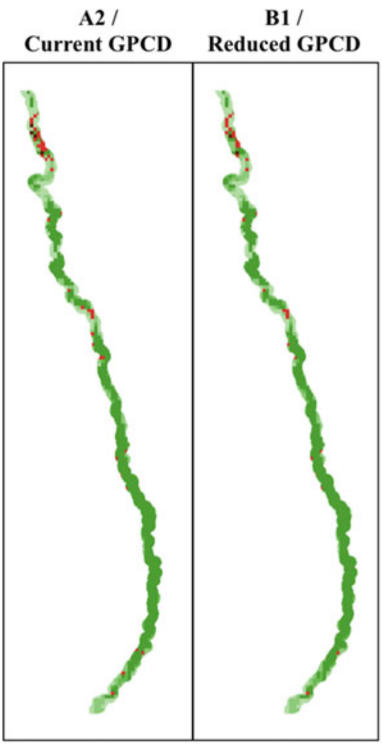

Fig. 2 Spatial distribution of deterioration in the riparian corridor for two population growth/water conservation scenarios. *Red pixels* represent areas that have been deteriorated at the end of a 50-year simulation

3 Bayesian Belief Networks

One tool that can be used to address uncertainty is Bayesian Belief Networks (BBNs). Bayesian Belief networks are a type of statistical model that represents conditional probabilities of factors via a directed acyclic graph. A Bayesian network has three components: nodes, links, and probabilities. Nodes are key factors in a system that can be either discrete or continuous, while links define the belief relationship between nodes. Within each node lies a set of probabilities that define the relationships. A unique probability specifies the likelihood a node will be in a certain state for each combination of states from influential nodes. The set of probabilities are called conditional probability tables. In this application, the change in one variable will affect the probability of a second variable taking place. Bayesian networks are unique in that they can use incomplete data, combine knowledge from diverse sources, from human experts and empirical data, and represent both quantitative and qualitative data (Bromely et al. 2002).

Coupling ABMs and Bayesian Belief Networks create powerful new insights and tools for studying and managing natural resources. Bayesian Belief Networks are typically developed with the help of experts in a system, because they are the most knowledgeable on the components and interactions in the system. Bayesian Belief Networks are especially useful when there a lot of interlinked factors, such as in complex systems, or if data is scarce and unreliable. Bayesian Belief Networks' probabilistic-based nature allows subjective beliefs about the system to be explicitly quantified. Characterizing expert opinion starts with developing acyclic maps, or mental maps of cause and effect, in both policy decisions and system processes (Tolman 1948; Axelrod 1976).

Bayesian causal networks are composed of three features: nodes, links, and probabilities. Nodes represent system variables and can have either discrete or continuous states. For example, a discrete amount of pesticide application could be below average, average, or above average whereas a continuous amount of pesticide application can be binned across a full range of application values. Links represent causal relationships between two nodes. A link, for example, from pesticide application to the amount of pests would describe the effect of the amount of pests caused by pesticide application. In Bayesian networks, the "effect" node (i.e., amount of pests) is described as a child of the parent "cause" node of pesticide application. Within each node lies a set of probabilities that defines the relationships between parents and their children. A unique probability specifies the likelihood a child will be in a certain state for each combination of parent states. The set of probabilities are called conditional probability tables (CPTs). In order to populate the CPT with data, we would need to find the probability of above average, average, and below average amount of pests for each state of pesticide application.

The combination of nodes and links create a directed acyclic graph, the structure of a Bayesian network. When developing the structure of a Bayesian network, it is important to minimize the number to nodes to the least number needed to accurately describe the system, which increased comprehensibility of the network for stakeholders. The incorporation of conditional probabilities tables transforms the structure into a functioning Bayesian network. At this point, a Bayesian network can be analyzed. By changing the state of a parent node, one can observe its effects throughout the network. Because perfect knowledge of a parent's state is rare, probability distributions across a parent's state can be used as input in Bayesian networks, incorporating uncertainty.

3.1 Acyclic Graph Creation

The structure of the Bayesian Belief Network was developed through a series of stakeholder workshops. In a workshop held January 2014, stakeholders from a variety of interest groups, including but not limited to ranchers, real-estate developers, city planners, and environmentalists, were asked to list potential policies, laws, and actions that would have an effect on the Upper San Pedro River Watershed. From their lists, stakeholders were then asked to plot each policy on a chart of probability and impact (Fig. 3). The chart was delineated into nine quadrants: low, medium, and high impact vs. low, medium, and high probability. From this delineation, the stakeholders identified 27 potential policy scenarios that would have a medium to high impact on the local system would they be applied (Table 4). The impact matrix elucidated two main themes of potential policies: water conservation and population growth regulation. The topics "Population Growth" and "Water Conservation" were chosen as action policies that were considered to be potentially the most impactful on the watershed.

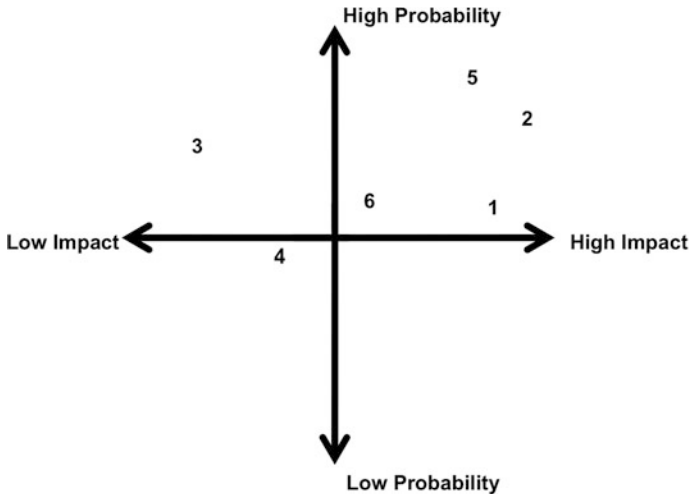

Fig. 3 Chart of impact vs. probability of occurrence from which potential policies, laws, and actions were plotted

Table 4 Stakeholder-defined polices, laws, and actions that would have a medium or high impact on the Upper San Pedro River Watershed, delineated by personal beliefs on the likelihood of being enacted

	Impact		
Occurrence probability	Low	Medium	High
High		Watershed-wide water conservation measures	Golf course irrigation improvements
			No net loss of groundwater
			Loss of private property rights
			Population growth
Medium		Mining	Increased water prices
		Increased tourism	Longer grazing season
		Creation of state water augmentation authorities	Improved fire management
			Regulations on population growth
			Decreased influence of Endangered Species Act
			Increased water use in Mexico
			Drought
			New subdivisions along the Upper San Pedro River
			Increased federal regulations
			Endangered species delisted
			Federal exemptions from environmental laws (e.g. border patrol)
			Federal government does not pursue water rights
			Establish a water conservation district in Redington
Low		Agriculture education	Local brush management
		Land-use planning	Decreased regulation
		Water importation	Reduction of litigation via environmental groups
			Recognizing the relationship between surface and groundwater

In a second stakeholder workshop, held January 2015, the same assemblage of stakeholders was invited back to further develop the network. The two action policies were explored within the context of the water management objective of minimizing further deterioration of the riparian corridor. Backwards development of the Bayesian Belief Network identifies under which conditions the two action policies would be enacted. In this regard, the stakeholders were asked "Under what conditions would water conservation be achieved?" and "What are some of the best ways to regulate population growth in the watershed?" For water conservation, two responses were recorded as nodes in the network: Increased Water Prices and New Water Conservation Programs. The responses for population growth fell into two of the three categories used by: domestic migration, such as closing Fort. Huachuca, regulating land-use, or encouraging economic development, and fertility, such as restricting government services (EPA 2009). All responses were recorded as nodes, and links were drawn between responses and the corresponding action policy. After all links are drawn, the structure of the Bayesian network is complete.

3.2 Conditional Probabilities

The goal of developing the Bayesian network is to create a unique probability of an environmental or social factor being in a certain state, in this case the percent of the riparian corridor that will show deterioration in the next 50-years. In order to fill out the conditional probability table of the effect of Population Growth and Water Conservation on the Riparian Corridor, 25 replications of all combinations of population growth projections and per capita water use (Current vs. Target (20 % reduction) GPCD) were simulated in the agent-based model. The percent of runs that resulted in 3–4 %, 4–5 %, or 5–6 % deterioration of the riparian corridor were recorded.

The conditional probability table between fertility, domestic migration, and population growth was set to match conditions described in ICLUS (EPA 2009, Table 1). For example, if fertility = low and domestic migration = low, then the likelihood that the population growth projection is B1 is 100 %.

The relationship between Increased Water Prices and Water Conservation was defined so each 10 % increase in price would result in a 3.3 % reduction in water demand (Olmstead et al. 2007). The probability of Water Conservation being in the "Current GPCD" state when no new programs are introduced was 100 %, less effects from Water Prices. If new water conservation programs were strong, the goal of reaching the Target GPCD was 100 %. If New Water Conservation Programs were weak, the probability of reaching the Target GPCD was 50 %. The Bayesian belief networks were developed using GeNIe, a Bayesian network software tool (http://genie.sis.pitt.edu/).

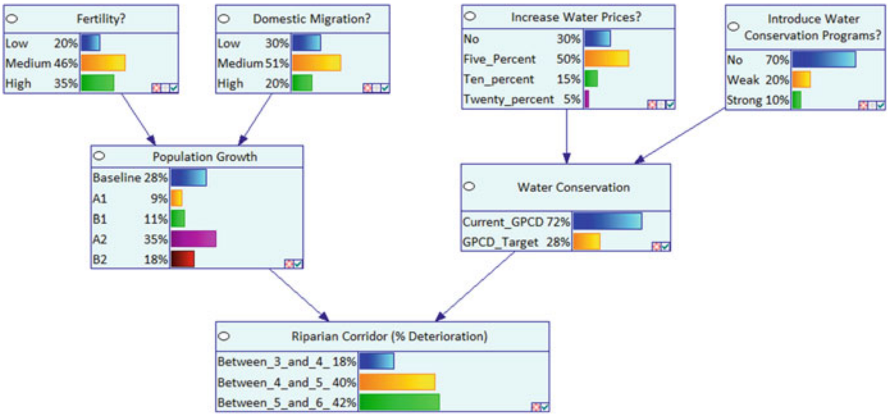

Fig. 4 Bayesian belief network of policy decision-making when there is a poor likelihood of strong water conservation programs being enacted

3.3 Bayesian Belief Network of Policy Decision-Making in the Upper San Pedro River

Once complied, the Bayesian Belief Network automatically calculates the probability of different levels of deterioration occurring in the riparian corridor in response to user-defined states of parental nodes "Fertility", "Domestic Migration", "Increased Water Prices" and "Introduce Water Conservation Programs". To illustrate how a decision-maker in the Upper San Pedro River Watershed could utilize the Bayesian Belief Network, we can imagine the decision-maker deciding whether it would be worthwhile to introduce new water conservation programs. Holding all other parental nodes constant, the decision-maker and alter the probability distribution of "Introduce New Water Conservation Programs" towards a low likelihood of any being enacted (Fig. 4). Once updated, the Bayesian Belief Network will calculate a probability distribution of the percent of the riparian vegetation experiencing deterioration. In this case, there is 42 % likelihood that deterioration will exceed 5 %. Contrast this to altering the probability distribution of "Introduce New Water Conservation Programs" to a high likelihood of strong water conservation programs being enacted (Fig. 5). Under this scenario there is only 10 % likelihood that deterioration will exceed 5 %.

4 Conclusions and Further Work

The agent-based model simulations demonstrated that in all scenarios, Marsh vegetation will have the greatest net loss, while *Tamarix* will experience the greatest gain. As a policy decision-maker in the Upper San Pedro River Watershed, the

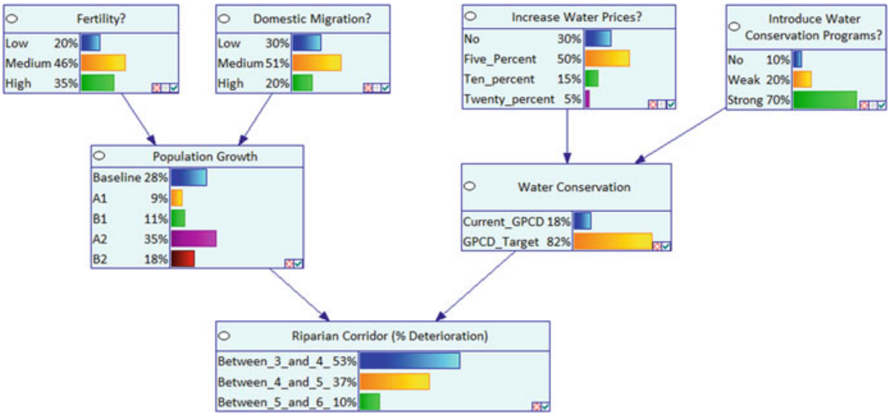

Fig. 5 Bayesian belief network of policy decision-making when there is a high likelihood of strong water conservation programs being enacted

results of the agent-based model may be discouraging. A strong reduction in water use only results in 1 % reduction in the amount deterioration of the riparian corridor. If new water conservation policy is passed, policy regulating population growth does not appear to have an appreciable effect on the riparian corridor. The lack of strong differences in the two per capita water use scenarios is likely due to the nonlinearity in the ecological system. Since vegetation communities change in response to a particular depth-to-groundwater, the model doesn't differentiate between large variations in groundwater change, just whether it has hit a threshold. In other words, the Current GPCD may have had a much larger impact on depth-to-groundwater relative to the Reduced GPCD, but as long as they both passed the Cottonwood-*Tamarix* threshold, no differences between the two scenarios would be seen.

The spatial distribution of deterioration of riparian vegetation is highly autocorrelated; most vegetation community changes occur in a small stretch of the river. By losing desired vegetation in a solid stretch of the riparian corridor, the model shows that desirable habitat may begin to fragment. The segregated areas of marsh vegetation north and south of the deteriorated stretch may not have a large impact on highly mobile species, such as birds, but may be important for other species that may not be able to travel safely between sections. The results also demonstrate one of the lesser-known benefits of spatial modeling, in that it is exposing that this area is in a state of transition and therefore a good site to focus on for environmental change research.

In the Bayesian Belief Network, the network was used to evaluate the effects of multiple policy options on riparian vegetation. The BBN showed how changing the likelihood of new water conservation programs could alter the probability distribution of percent deterioration of the riparian corridor. This approach highlights both the uncertainty of predicted effects but also how to incorporate uncertainty of the policy decision-making process itself (Spiegelhalter et al. 1993). This is especially useful for decision-makers in that they can balance the desirability of an outcome against the chance the outcome will be successful.

When building models that are designed to help decision-makers, it is important that building and sharing results of the models are easy to communicate. The graphical-based form of acyclic maps makes them accessible to a wide range of people, including those who are not familiar with modeling approaches, because the logic of nodes and links can be clearly illustrated (Elsawah et al. 2014). The process of building the network, although time-intensive, can also be used as a learning tool for non-experts. The development of the acyclic maps requires individuals to conceptualize the complex system and its interrelatedness. The increased understanding on the interactions within the system raises awareness for stakeholders on how decisions may impact the system as a whole, including factors not included in the model (Cain 2001). Because acyclic maps are accessible, results of the Bayesian Belief Network are easy to explain and have high transparency (Elsawah et al. 2015). By linking Bayesian Belief Networks with ABMs, particularly ones that are spatially-explicit, the outputs of the model can have a greater impact on the general public.

In developing a Bayesian Belief Network for policy decision-making, the network structure encourages exploring more management alternatives, and can accommodate additional factors if they are found to be important at a later date. The Bayesian Belief Network provides the opportunity for stakeholders and decision-makers alike to test proposed management strategies prior to application. Additionally, concerns for both social and ecological components can be evaluated, allowing for an examination of trade-offs of management decisions (Pahl-Wostl et al. 2008). Bayesian Belief Networks can also estimate the effect of a management decision to factors that are not directly linked to the decision (Bromely et al. 2002; Giordano et al. 2010; Sedki and de Beaufort 2012). Alternatively, Bayesian Belief Networks can simply provide optimal decisions based on the information provided. However, a coupled ABM—Bayesian Belief Network model cannot be over relied upon to make decisions for decision-makers, because it may not include all relevant factors. Instead, decision-makers should assess the cumulative knowledge of the system to make better decisions.

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Part II
Approaches for Understanding, Modeling, Forecasting and Mastering Complex Systems

Dialectical Systems Theory as a Way to Handle Complex Systems

Matjaz Mulej, Zdenka Ženko, and Nastja Mulej

Abstract Complexity includes attributes of entanglement that result from relations and processes. It can be found in nature, society, organizations and technology. Humans specialize in their education, knowledge and experience. This makes specialists one-sided and thus hardly able to handle the given complexity, unless one applies one or more of the versions of systems theory, which support interdisciplinary creative cooperation, such as the Dialectical Systems Theory. The related applied methodologies and methods are also very useful, because they can be used without too much complexity of theories.

1 The Process of Human Handling of Complexity

The term system has many contents that differ from each other crucially—from calling everything a system, when it is considered, via reducing the term system to complex features and to the perception that a system is a mental and/or emotional picture of the object under consideration (Mulej et al. 2013). Therefore we will not speak of complex systems, but of complexity, here.

Complexity is a fact resulting from relations and processes, not single parts alone; entanglement inside them is called complicatedness (Mulej et al. 2013). Complexity can be:

– Natural;
– Social;
– Organizational;
– Technological.

Complexity of reality causes human specialization of knowledge into parts of real attributes. This leads to one-sided perceptions of reality, limited inside

M. Mulej (✉) • Z. Ženko
Faculty of Economics and Business, University of Maribor, Maribor, Slovenia

N. Mulej
Nastja Mulej s.p., Ljubljana, Slovenia

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one's specialization. Unfortunate oversights along with insights happen therefore causing the danger of crisis, of which the current global socio-economic crisis is an extreme case, putting the survival of humankind under question mark. An urgent need for requisite holism to reduce/abolish oversights results causing an urgent need for interdisciplinary cooperation aimed to cover all crucial attributes. Wiener, Bertalanffy and other crucial authors perceived such a danger in the time of the Second World War, which was in practice leading to cybernetics and systems theory as a number of theories against over-specialization (François 2004). The theory of /requisite/ wholeness of outcomes based on /requisite/ holism of approach, such as Mulej's Dialectical Systems Theory (DST) was and is difficult for the normal contemporary over-specialists, who were/are not educated for interdisciplinary creative cooperation. They need ethics of interdependence of mutually different specialists, making them cooperating specialists. Since 2010 application of systems theory VIA social responsibility (SR) (ISO 26000) is enabled by ISO (ISO 2010) with its basic concepts: (1) interdependence, and (2) holistic approach, too, covering informal systemic behavior.

Perception of complexity opens issues of both the knowledge and values as the basis for one's decision on what is found important, interesting, beloved, inside ambition, etc. or not.

Perception of complexity that reaches beyond human capacity of understanding and mastering makes one's selection of the really existing attributes into the (1) considered and (2) not considered ones. This fact opens the issue of the level of simplification as a process of the following steps: (1) object in reality, selected for observation and mastering; (2) selection of ones' viewpoints for dealing with the selected object; (3) selection of the considered interdependencies between the selected viewpoints; (4) introduction of the 'dialectical system' for consideration and mastering of all crucial and only crucial attributes; (5) if this is found too complex, selection of a single viewpoint; (6) introduction of the selected 'system' as the mental picture of the selected object limited to the selected viewpoint, never equal to the object under consideration/mastering; (7) modeling of the 'system' with a model presenting the 'system' in a simplified way for communication with other specialists as a basis for their creative cooperation; (8) diminished/erased over-specialization, over-simplification, over-trivialization, oversights and resulting endangered survival of each participant; (9) closer to the way out from crises by a (10) non-technological innovation summarized as the transition from ethics of independence (except the legal one, preventing abuse and misuse e.g. by bosses) and ethics of dependence (of e.g. obeying only subordinates, thus being granted the right of irresponsibility and no initiative or innovation, i.e. leaving creativity to ones' free time and poor working in duty time), to ethics of interdependence. For details see Mulej et al. (2013).

The bigger is the complexity in the given case, the bigger is the need for interdisciplinary cooperation and therefore is there a bigger need for ethics and practice of interdependence and a bigger need for practicing the seven principles of social responsibility from ISO 26000: (1) accountability, (2) transparency, (3) ethical behavior (i.e. reliability, honesty, care for each other and nature), (4) respect for stakeholders (not owners only), (5) respect for the rule of law, (6) respect for international norms, and (7) respect for human rights (ISO 2010). On this basis, there is a bigger need for open communication causing a bigger need for capacity to listen and hear, especially the ones who disagree and have alternative suggestions, because they apply different selected viewpoints. This interdisciplinary cooperation enables humans to complete up their original suggestion and the list of them. This is easier to attain, once one perceives one's bigger need for the methodological support, e.g. by USOMID (Mulej et al. 2013 and earlier) and/or 'Six Thinking Hats' (De Bono 2005) and other methods supportive of the creative cooperation for mastering the given complexity.

Albert Einstein has put it well: 'Let us simplify as much as possible, but not more than that'. This is what the Dialectical System Theory is about, methodologically.

2 Dialectical Systems Theory

Mulej (1974 and later on) made the dialectical system concept (instead of a General System Theory one, see Bertalanffy 1968) methodologically supported by becoming, formally, a dialectical system of three elements and three relations, in general. They are supposed to both influence humans as observers, thinkers, decision makers, and decision implementers, and to help them attain the requisite holism of their behavior to enable the best possible results. Success is thus attained with no excessive effort and no crucial lack of insight and influence; this requires a well-managed process in which all crucial steps, interdependences and synergies are considered. In order to attain such a success, human attributes of both decision makers and decision implementers must support creativity and requisite holism with co-operation of complementary professionals. In this effort, it helps a lot, if application of theory can take place in an informal style. This is why there are three relations and three elements in the Dialectical Systems Theory as a dialectical system: all of them are both essential and sufficient; in other words, the Dialectical Systems Theory matches criteria of requisite holism (Mulej et al. 2013).

The law of requisite holism demands the author/s of the definition of a system representing the object under their consideration and/or control to clearly state what part of attributes of the object is included into their system; this is the mental picture of the object under consideration and/or control; one must do one's best to fight over-simplification by all available/crucial knowledge and skills as well as by ethics of interdependence.

The law of entropy reflects the reality in which there is a permanent tendency toward destruction, which demands requisite holism and innovations permanently; the latter ones have conditioned survival since the times humankind has given up human's adaptation to nature.

In the context of the *law of entropy* we have to consider, think and rethink: shall we induce the changes; shall the changes be hindered; shall we try to attain the equilibrium. The mentioned possibilities are showing the possible re-action to the changes: in the first case we strengthen them, in the second case we try to suppress them and in the third case we try to minimize their impact. Why the holism and innovativeness as the human attribute matters? With both of them we can act against the entropy. Although the innovation should not be linked to small technical and technological novelties elaborated without the formal duty, the innovations are still described and interpreted in those terms.

The three relations making the three laws work in reality under human control are: (1) ten guidelines for definition of the starting points of the human work and cooperation process and resulting goals, (2) ten guidelines for realization of the agreed-upon goals, and (3) the USOMID methodology for the application of the dialectical systemic behavior.

Now, the dialectically systemic behavior can be attained, or supported at least, by the concept of social responsibility summarized in ISO 26000 (ISO 2010).

3 Summary of Social Responsibility

SR became increasingly important in recent years, especially after a very long economic growth cycle had ended with 2008-crises. During our research on SR in 2009 we found on e-browser Google 25 million hits. On May 7th 2010 we found 116 million hits, and on June 27th 2011 137 million hits, in June 2012 beyond 400 million. Then we gave up our hope to read them. Contributions on SR are too many to read. Let us take only the official definitions:

- The EU's (2011) definition is clear: SR is responsibility for one's impacts on society and nature. It is quite obligatory: EU member-states and big companies should promote SR as its role models—for clear economic reasons, i.e. to solve the current socio-economic crisis.
- ISO 26000 requires a *holistic approach* (based on *interdependence*) and includes *seven content areas*: (1) organization, management and governance, (2) human rights, (3) labor practices, (4) environment, (5) fair operating practices, (6) consumer issues, and (7) community involvement and development.
- This requirement is supported by *seven principles*: 1. accountability, 2. transparency, 3. ethical behavior, 4. respect for stakeholder interests, 5. respect for the rule of law, 6. respect for international norms of behavior, and 7. respect for human rights.

We find the two concepts linking them at least equally important:

1. *Interdependence*, and
2. *Holistic approach*.

- Chapter 7 in ISO 26000 suggests *seven steps of the procedure of introduction of SR into the organization*. SR is too complex to be applied in a short and simple procedure.

Thus, the law of requisite holism (RH) and ethics of interdependence are reinforced on the global level. They are not valid for enterprises only, but also for governments, i.e. nations and peoples around the world, if they want to survive. Human management of social and organizational complexity of life matches the seven SR principles insufficiently.

International Standard ISO 26000 is a great guidance to SR, actually to (dialectically) systemic behavior. Though, ISO 26000 is guidance, *not* an international *law*, even less a supra-national law, but the market requires it. Including the Dialectical Systems Theory and its methods helps the stakeholders to more easily accept, practice and demand SR globally. We see in practice, that this can be attained on an informal basis, too, which we could suggest, if we had room (Štrukelj 2015). The point is not in SR as something self-sufficient, but in its role of the systemic/DST alternative to the neo-liberalistic blind alley. A smaller complexity can thus replace a complexity erasing humankind.

It is also important that no certification for ISO 26000 is possible, but certification for management of ISO 26000 has become possible in 2011 (IQnet 2011). This may fortify systemic behavior, albeit in a (too) slow and rather late and complex invention–innovation–diffusion process (Ženko and Mulej 2011a, 2012).

The essence of the considered complexity lies in the fact that social responsibility means a revolution in human values, culture, ethics and norms from over-specialization to interdependence and mutual consideration. Great examples can be followed to learn from them.

- Collins (first with Porras, then alone, 1997; 2001; 2005) found with their teams of empirical practice researchers that “visionary companies” have been best off over an entire century, based on their SR governance and management practices.
- US Air Force General Wilbur L. Creech (1994) showed, after 47 years of experience that he had survived thousands of flights by cooperating with, rather than one-sidedly commanding, his teams: he used ethics of interdependence for RH.
- Mondragon is an exemplary community in the Basque region of Spain, which during the past plus five decades has successfully applied co-operative ownership and management to its industrial production, schools, housing, banking, etc. Book by Dyck and Mulej, ed. (1998) includes this and 30 other case studies. Indirectly these are cases of various consequences of SR practices.
- Florida (2002) shows that the US regions with the highest 3T levels (tolerance, talents, technology) attract the most creative/productive people and enjoy the highest standard of living. Tolerance receives support from interdependence and supports holistic approach.
- Sachs’ (2011) delivers data and analysis showing why the US is in deep crisis, to which SR/RH is the solution. Difficulties result from too poor SR practices due to one-sidedness.
- Along with these models EU suggests all the use of ISO 26000.
- Roubini’s remark (2010: 10) that managers’ pay needs a longer-term basis is crucial.

– To persuade people one might use data summarized from five further books in Mulej's review (2010).
– The process of making SR a prevailing management and governance practice should be considered a complex non-technological invention–innovation–diffusion process applying the Dialectical Systems Theory.

4 Brief Suggestion Concerning Application of Social Responsibility in Management of Complexity

All three sets of seven items in ISO 26000 may be practiced informally, which is OK, too. The more they have been practiced, the closer the cooperating humans, organizations, countries may come to realization of the basic three postulates of social responsibility:

a. Interdependence (and ethics of interdependence rather dependence and independence);
b. Holism (actually: requisite holism, because more cannot be attained); and
c. Responsibility for one's impact on society.

Management of complexity requires and supports all three of them much more than management of simple processes does.

USOMID and 'Six Thinking Hats' have been applied in separation for nearly three decades, before one made a synergy. They might be helpful in this case, too. We have no room for details here.

'Diffusion of innovation' as a methodology which supports dissemination of an innovated practice, including a dialectically-systemic behavior, might be helpful in this case, too. We have no room for details here (Ženko and Mulej 2011a, b, 2012).

The necessary mutual trust receives support from pubic awards for social responsibility, such as the Slovene award for requisitely holistic SR 'Horus' (www.horus.si).

5 Methodological Support to Efforts for Social Responsibility and Dialectically Systemic Behavior

The crucial ideas of social responsibility need methodological support to become reality in company practice. This means that governance and management do need the knowledge briefed above here, but also methodological knowledge. We do not have room for all ideas suggested by Štrukelj (2015). We shall keep to our own experiences. Both De Bono's "Six Thinking Hats" (2005) and Mulej's USOMID (1982) methodologies experienced thousands of successful applications for decades.

To avoid 'fighting' rather than creating in sessions etc., it makes sense to use both methodologies in a synergetic combination. Here we will discuss our concept of this combination.

5.1 Summary of the Essence of USOMID

Acronym USOMID denotes "Creative Co-operation of Many for Innovativeness at Work" (Mulej 1982). It denotes a methodology and method that has been developed to make application of Mulej's Dialectical Systems Theory (DST) feasible with no word of theory (Mulej et al. 2013). In DST one considers starting points, both objective and subjective parts of them before objectives definition. The objective ones cover conditions—(a) needs and (b) possibilities, e.g. typical of an innovative society. The subjective ones cover human attributes summarized as (1) knowledge on "What" that means contents; (2) knowledge on "How" i.e. methods, techniques; and (3) values and emotions (to respond to question "Why do/should we like/dislike to do . . . ?"). All five reflect in components of USOMID, with which starting points become more concrete in line with the given conditions. They are interdependent. Thus, one attains requisite holism, while one-sidedness is dangerous and total holism is unattainable.

The general methodical knowledge is called in this case the *USOMID/SREDIM* PROCEDURE, which is used by co-workers, organized in *USOMID circles*. This can apply to solving and complex problems, as decades of experience have demonstrated.

5.2 USOMID-SREDIM Procedure as the General Method for Creative Work and Co-operation in the USOMID Circle

Now we are focusing on contact points of USOMID in Six Thinking Hats (6TH) methodology. This is why, among attributes of USOMID, we find procedure the most interesting here. It might namely complete up the so-called Blue Hat, while the other five hats would complete up the work and co-operation by USOMID. (We will brief 6TH later.)

The acronym SREDIM denotes six steps of the procedure, while acronym USOMID denotes that it is not only process of *work*, but also of *co-operation* that does not exist in the original SREDIM procedure (see: Mogensen 1981).

In step S (select problem) the unit's coworkers (or students in a team) first collect suggestions what are problems worth solving and opportunities worth developing. The created list offers every individual a chance to choose what problem/opportunity he or she wants to help solving/developing. Volunteers make circles and decide on their own problem/opportunity selection. (All six hats are usable now.)

In step R (record data) the circle collects data about their selected problem. Now they can support their work with programs from DST, which we do not summarize here. In this step no data receive the question ‘why’ or any form of doubt. This is the positivistic, uncritical phase. (It is similar to thinking under the white hat.) Criticism will have its turn in the next phase.

In step E (evaluate collected data) namely the question ‘why’ becomes central. Circle members have no solution, only unevaluated data. Data must be analyzed to bring participants later on more easily to a solution that will not be fictitious, but making sense. This phase will draft several possible solutions. (In it, all six hats may apply, but mostly the red, green, yellow, and black ones do, as phases.)

In step D (determine and develop solution) the circle will first assess which drafted solution is relatively most realistic and promising, how can several of them be combined into a new synergy, etc. Then the circle will try to develop the selected draft solution to a workable, usable, and potentially useful/beneficial one. (Again all six hats may apply, but mostly the red, green, yellow, and black ones do, as phases.)

In step I (implement solution) the circle tries to have their selected solution applied in reality (on a prototype level, at least). If people feel they are solution’s (co)-authors, one will probably not have to break their opposition. If one imposes the new solution, only people enjoying a big trust may succeed. Therefore this phase may have to be a project in its own right. (This phase is no longer covered by the Six Hats; all six hats may apply, but mostly the red, green, yellow, and black ones do, as phases, for the preparation of a real-world implementation.)

In step M (maintain the introduced solution) one considers that the introduced novelty does not necessarily survive on its own. It needs maintenance. At the same time, this phase shows, what is a remaining or new problem/opportunity worth solving/developing. This brings us into the next cycle of application of the USOMID procedure. (Again, the six hats no longer cover this phase, but for preparation of maintenance all six hats may apply, but mostly the red, green, yellow, and black ones do, as phases.)

Concrete techniques for steps SREDIM are chosen in real time according to the problem type.

The four steps, which control *running* each of the SREDIM phases, are our addition (Mulej 1982; several books later on, including Mulej et al. 2013). We found them needed, because one otherwise has a good process of work with no creative co-operation, which is not enough. A brief comment:

1. *Individual brain writing* allows everyone to think at the same time with no waiting for the oral discussants to finish. Notes must have no signature and must be in capital letters or typed for contents to be easier to see, and the authors to be invisible.
2. *Circulation of notes* among circle members allows for synergy of notes. Everybody receives notes of all others, reads them and adds ideas surfacing in one’s head while reading (if any).

3. *Oral discussion* about the collected ideas follows, after everybody has used all notes once or twice. Discussion must synthesize the collected ideas toward a common opinion/finding. All six hats may apply, but mostly the red, green, yellow, and black ones do, as phases.
4. *Shared minutes/conclusions* result from synthesis of the attained conclusions. All six hats may apply, but mostly the red, green, yellow, and black ones do, as phases.

The focus of thinking is frame-worked by the current step of SREDIM, all the time.

Including all four steps of co-operation in the phase S makes USOMID different from the usual brainstorming in which somebody is in charge of imposing over the others what will be their topic. Imposing creates resistance, inhibiting devotion of co-workers creativity to the topic. They can find sufficient excuses to make it fail. USOMID prevents this difficulty, especially in combination with 6TH.

USOMID is mostly devoted to studying and innovating processes of creative work rather than of routine. Details cannot be included here. Principles of proceeding from a rough toward a detailed insight, causes tree etc. are used for authors to meet the entire dialectical system of preconditions of requisite holism at work. We cannot expose details here (see: Mulej et al. 2013). Neither have we room to include details about an even distribution of organizational jobs to all circle members. It evens burdens and allows everyone to control an organizational viewpoint of the shared process as well as to be creative as a circle member. There are 12 roles in the USOMID/SREDIM model, because the upper limit of circle-members number is 12 (the down limit being five). In the circle's meeting, there is another usual danger: some circle members may want to prevail and argue, which leads toward a one-way communication rather than to creative cooperation of all circle members. Cooperation receives support from the USOMID/SREDIM procedure and can receive additional support from the 6TH methodology.

5.3 Chances for Completing up USOMID by the SIX THINKING HATS

As we have briefed in Sect. 5.2, the USOMID model of creative co-operation enables smooth work covering several professional views and organized procedure, thus leading toward the law of requisite holism. This enables a lot of creativity and a lot of innovation, not invention only. A problem that has remained unsolved over all 30+ years is 1. relative waste of time, 2. fight/arguing and bad feelings. The organizational jobs are supposed to solve this problem, but it does not always work without trouble. This is where the 6TH applies.

The 6TH enters the scene as the third dimension along with SREDIM and the four USOMID steps in every-one of them (Table. 1). We hinted to it in Sect. 5.2. The 6TH namely enables all circle members to not argue, but to think *in the*

Table 1 Synergy of USOMID/SREDIM and 6TH methodologies in procedure of USOMID *(Matjaz and Nastja* 2006*)*

SREDIM Phases USOMID Steps Inside SREDIM Phases	1. Select the problem / opportunity to work on in an USOMID circle	2. Record data about the selected topic (no 'Why')	3. Evaluate the recorded data on the topic ('Why is central')	4. Determine and develop the chosen solution/s to the topic	5. Implement the chosen solution to the topic in reality	6. Maintain the implemented solution for a requisitely long term
1. Individual brain-writing by all in the organizational unit / circle	All 6 hats	White hat	All 6 hats, red, black, yellow, green first of all	All 6 hats, red, black, yellow, green first of all	All 6 hats in preparation of imple-mentation	All 6 hats in preparation of maintenance
2. Circulation of notes for additional brain-writing by all	All 6 hats	White hat	All 6 hats, red, black, yellow, green first of all	All 6 hats, red, black, yellow, green first of all	All 6 hats in preparation of implementa tion	All 6 hats in preparation of maintenance
3. Brain-storming for synergy of ideas / suggestions	All 6 hats	White hat	All 6 hats, red, black, yellow, green first of all	All 6 hats, red, black, yellow, green first of all	All 6 hats in preparation of implementa tion	All 6 hats in preparation of maintenance
4. Shared conclusions of the circle	All 6 hats	White hat	All 6 hats, red, black, yellow, green first of all	All 6 hats, red, black, yellow, green first of all	All 6 hats in preparation of imple-mentation	All 6 hats in preparation of maintenance

same direction, and to do so in terms of the exposed part of values rather than of knowledge. Thus, our tendency toward the requisite holism is not blocked. The six hats are namely neither used by one person each nor all at the same time, but all circle members use the same hat, and later on another one, at the same time, as phases. According to De Bono, this replaces the old western habit that the discussion participants close themselves in their respective viewpoints (like e.g. solicitors or politicians or armies or angry children) and fight for the upper hand rather than for mutual completion and shared and beneficial new solution (De Bono 2005). In other words, the 6TH supports well the creative cooperation, but from different viewpoints than the above-summarized attributes of USOMID do: 6TH points more to the values-and-emotion part of the human personality than to the professional part. Both of them are interdependent anyway.

As briefed above, USOMID contains roles for organizational jobs along the shared thinking. With these roles and the USOMID/SREDIM procedure USOMID covers the blue hat, but not the others. The white one may be visible in step 2 (Record data). Procedure USOMID-SREDIM may be better in providing a logical phases order, about which users of 6TH must and may decide on their own.

In 6TH all circle members think in the frame of the same hat. De Bono calls this manner "parallel thinking" that provides for the same orientation, i.e. looking for ideas and proofs. It lets nobody oppose each other. Hats enter the scene as phases, ruled by accents of thinking, thus providing the power of focusing, time saving, removal of "ego", neutrality and objectivity: one viewpoint in one moment (by phases—hats).

Obviously, all thinking hats are interdependent and used per phases. With some more detail they can be briefed as follows (details in: De Bono 2005, or any other edition of the book):

White Hat
- Facts, data in the given framework (=law of requisite holism);
- No interpretation—self-discipline (!)—facts, no possibilities/persuasions, verified data;
- An overview (="map") is made step by step;
- Mutual listening, no prior definitions and/or decisions;
- Practical orientation, all data;
- Like a computer.

Red Hat
- Feelings, emotions, intuition;
- No explanation why something is (dis)-liked;
- Beneficial, although not always precise, correct;
- Intellectual feelings too ("interesting");
- The opposite from the white hat, the irrational aspect of thinking;
- Emotions are unavoidable;
- Intuition that leads to a new view and thus to creativity;
- Opinion = assessment + interpretation + intuition = feeling;
- Emotion to be expressed without delay = background of thinking, values;
- Thinking leads to satisfaction (!!), but:

  Is it detrimental to others?
  Short term versus long term?

- Emotions cannot be logical; therefore no justification takes place.

Black Hat
- Pessimism; most frequently—precaution, security, possible dangers, in order to enable survival;
- Critical standpoint, deviation from expectation in order to act against mistakes;
- No exaggeration in order to prevent over-pessimism and abuse of caution;
- Criticism, but all remains logical, although from negative viewpoints;
- No equilibrium; weak points are stressed now, the yellow hat will stress strong ones;
- Doubt about strength of proofs ("Might we better switch to the while hat?") in order to lead to a requisitely holistic insight and assessment of the future situation;
- No limitation to criticism, a contribution is asked for!

Yellow Hat
- Optimism; advantages of the suggestion, positive thinking;
- How to implement the idea in practice?
- Sensitivity for the benefits of the idea;
- Care for making not only black views visible; correction of them, but not in the moment they are being expressed;
- Success; the unstoppable desire to implement the idea;
- Discipline! Conscious search for positive attributes, sometimes in vain, optimism may be exaggerated: "What action follows it now?"
  - Assessment of probability that it comes through;
  - Backing one's positive assessment with research;
- Constructive approach to strengthen efficiency of realization, but more important changes are not included now, they belong to the green hat.

Green Hat
- Energy, novelty;
- Creativity = the key part of thinking;
  - Deliberate;
  - Fantasy-based;
- Expose chances—to overcome obstacles that the black hat demonstrates;
- If energy is too abundant, one switches to the red hat to choose the framework of thinking;
- Use it, when experience no longer works well;
- Provocation included, research, risk as well;
- Lateral thinking (=step away with patterns in a new direction) (see also: De Bono 2006);
- Thinking about action, rather than assessment only;
- Logic of nonsense, provocation—"PO" = provocative operation, beyond "yes or now";
- Alternatives after some results;
- Skill + talent + personality, all of them are needed and interdependent.

Blue Hat
- Thinking about thinking;
- Conductor, control, organizing, double-checking;
- Initial hat/step—to define situation, intention, timetable, sequence of hat application;
- Group head is in charge of this hat all the time, others may intervene;
- At the end—conclusions, summaries;
- Focusing—questions, problem, tasks, procedures, tools;
- Observation, discipline.

The system/network of all six hats produced many successes in different practical cases for three decades around the entire world (De Bono 2005).

This methodology disables one-sided arguing. It makes room for all opinions and data to be presented by phases covered by 'thinking hats' in a well arranged procedure in which nobody has either the upper hand or subordination. One-sided, narrow interests that have caused all troubles and wars might be overcome—by informal dialectically systemic behavior. Complexity may be under human control with a higher probability than otherwise.

6 Conclusions

The natural, societal, technological and organizational complexity are crucial sources of troubles in human life. Therefore humans develop methods and methodologies to control complexities of any kind. One-sided specialization that is the current reality of human knowledge causes less troubles, if it is applied in creative interdisciplinary cooperation. The Dialectical Systems Theory is one of the systems theories that has proven in four decades of application to be a beneficial support to attainment of the requisite holism. The effort may be simplified by application of the concept of social responsibility and by methods of USOMID and Six Thinking Hats, especially in their synergy. Thus, complexity can be mastered better.

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Reducing Complexity of Nonlinear Dynamic Systems

Anca Maria Nagy-Kiss, Georges Schutz, Benoît Marx, Gilles Mourot, and José Ragot

Abstract The complexity problem of nonlinear dynamic systems appears in a great number of scientific and engineering fields. The multi-model, also known as polytopic approach, constitutes an interesting tool for modeling dynamic nonlinear systems, in the framework of stability analysis and controller/observer design. A systematic procedure to transform a nonlinear system into a polytopic one will be briefly presented and illustrated by an academical example. This procedure gives the possibility of choosing between different polytopic structures, which is a degree of freedom used to ease the controllability, observability, stability analysis studies. In addition to that, the system transformation into polytopic form does not cause any information loss, contrarily to most existing studies in the field.

In the second part of this chapter, a discussion about multiple time scale nonlinear systems, also known as singularly perturbed systems is proposed, by eliminating some structural constraints and by performing the identification and the separation of the time-scales. Robust observer synthesis with respect to internal/external perturbations, modeling parametrization errors and unknown inputs are presented for the estimation of different variables of interest, the state variables.

The above-mentioned points will be applied to an activated sludge wastewater treatment plant (WWTP), which is a complex chemical and biological process. The variations in wastewater flow rate/composition and the time-varying biochemical reactions make this process nonlinear. Despite the process nonlinearity and complexity, there is a need to control the quality of the water rejected in the nature by the WWTPs in order to achieve the requirements of the European Union

A.M. Nagy-Kiss • G. Schutz
Environmental Research & Innovation Department, Luxembourg Institute of Science and Technology, 5, avenue des Hauts-Fourneaux, L-4362 Esch/Alzette, Luxembourg
e-mail: nagyanca84@gmail.com; georges.schutz@list.lu

B. Marx • G. Mourot • J. Ragot (✉)
Université de Lorraine, CRAN, UMR 7039, 2 avenue de la Forêt de Haye, Cedex 54516 Vandoeuvre-les-Nancy, France

CNRS, CRAN, UMR 7039, Vandoeuvre-les-Nancy, France
e-mail: benoit.marx@univ-lorraine.fr; gilles.mourot@univ-lorraine.fr; jose.ragot@univ-lorraine.fr

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in terms of environmental protection. To this end, a Benchmark, proposed by the European program COST 624 to asses the control strategies of WWTPs, is used as an example in the present chapter.

1 Problem Formulation

This chapter explains how the multi-model approach [also called polytopic (Angelis 2001) or Takagi-Sugeno approach (Takagi and Sugeno 1985)] can be used to model dynamical nonlinear systems, for observer/controller design or fault diagnosis purposes.

It is known that the dynamical and the nonlinear attributes are features of most existing technological or environmental processes. The modeling complexity problem is consequently an important element in a great number of scientific and engineering fields. When dealing with such systems, there is a necessity to develop systems operating over a wide range of functioning conditions and handle, in a most simple way, this complexity. Generally, a nonlinear system under the state space form is written as:

$$\dot{x}(t) = f(x(t), u(t)) \tag{1a}$$

$$y(t) = g(x(t), u(t)) \tag{1b}$$

where $x(t) \in \mathbb{R}^{n_x}$ is the system state, $u(t) \in \mathbb{R}^{n_u}$ is the known input, $y(t) \in \mathbb{R}^{n_y}$ is the measured output and where f and g are nonlinear functions depending on the states x and inputs u. In real processes, these functions can be very complex and impossible to exploit for control and diagnosis purposes.

In the last decades, the multi-model approach seems to be an interesting tool to deal with complex nonlinear systems and thus has been intensively studied. It is the reason why it has been chosen for our recent research studies.

The basic principle of the multi-model approach is to replace an unique global model, as the one described by (1)—considered overly complex to be used as it is for different objectives, such as control, observer synthesis or fault diagnosis—by a set of simpler linear models defined as submodels. Roughly speaking, in the earlier works (Takagi and Sugeno 1985) each submodel describes the behavior of the considered process around a particular operating point and, thanks to a time varying interpolation mechanism between the different submodels, the global multi-model structure represents the original nonlinear model. Since the submodels are linear, it is an efficient way to address nonlinear problems by slightly adapting linear techniques (Nagy et al. 2010).

The multi-model formalism is consequently based on time-varying interpolation between a set of linear sub-models. In the state space representation, the multi-model structure is presented as follows:

$$\dot{x}(t) = \sum_{i=1}^{r} \mu_i(z(t)) \left[A_i x(t) + B_i u(t)\right] \tag{2a}$$

$$y(t) = \sum_{i=1}^{r} \mu_i(z(t)) \left[C_i x(t) + D_i u(t)\right] \tag{2b}$$

where r is the number of submodels, the weighting functions $\mu_i(z(t))$ depend on the premise variables $z(t)$ and represent the weights of the submodels defined by the known matrices (A_i, B_i, C_i, D_i). The premise variables may depend on measurable signals (e.g. the system inputs or outputs) and/or on unmeasurable signals (e.g. the system state variables).

The functions $\mu_i(z(t))$ have the following properties:

$$\sum_{i=1}^{r} \mu_i(z(t)) = 1 \text{ and } \mu_i(z(t)) \geq 0, \quad \forall t \in \mathbb{R}^+ \tag{3}$$

As mentioned in Chap. 14 of Tanaka et al. (2001), every nonlinear system can be written as a multi-model on a compact set of the state space, by using the so-called sector nonlinearity approach, that will be later on presented. The drawback of this technique is that no systematic choice of the premise variables has been realized. The choice of the premise variables plays a central role in the derivation of a the multi-model, since it impacts the structure of the submodels and thus on their use for performance analysis and observer/controller design. Other techniques to obtain a multi-model exist, such as linearization of the nonlinear model around one/several operating points, or dynamic linearization near arbitrary trajectory (Mourot et al. 1999), system identification using experimental data (Johansen et al. 2000). Nevertheless, these different techniques are not general and systematical methodologies, depending, on one hand, on the choice of operating points (trajectory), and on the other hand, on the available data.

An analytic multi-modeling procedure with a motivated choice of the premise variable is presented in Nagy (2010a) and will be used as a nucleus point for modeling in this chapter. The proposed methodology avoids the inconveniences of the previously mentioned existing works: the choice of the linearization points is not necessary. and the transformation is realized without loss of information. Indeed, the obtained system has exactly the same dimension [simplification of MM systems by model order reduction is dealt in Marx (2015)] and state trajectory as the initial system. The complexity reduction comes from the fact that many analysis and/or design methods dedicated to linear systems have been extended to MM systems, and thus can be used to deal with nonlinear systems. The main points of these analytical rewriting technique will be described, illustrated and discussed in Sect. 2.

2 Analytic Procedure to Obtain Multi-model Structure

This part is dedicated to the general methodology of transforming a given nonlinear model (1) into a multiple model. The transformation is realized without loss of information, the obtained system has exactly the same state trajectory as the initial system. The proposed method is analytical, and the obtained multi-model is equivalent to the initial nonlinear system.

Given a nonlinear system (1) with bounded nonlinearities, a multi-model state representation (2) can be obtained. This multi-model representation constitutes a linear parameter varying (LPV) system because the convex combinations of constant matrices calculated from the polytopes vertices give rise to matrices with variable parameters. The vertices are obtained using the convex polytopic transformation (CPT), given by Lemma 1. The constant matrices define the submodels and the nonlinearities are rejected into the submodel weighting functions. The multi-model obtained with this method is not unique: it depends on the choice of the lower and upper bounds of the nonlinearities used in the CPT and on the factorization used to rewrite the nonlinear system as an LPV model.

Lemma 1 (Convex Polytopic Transformation (Tanaka et al. 2001; Wang et al. 1996)). *Let $h(z(t))$ be a bounded and continuous function from $[z_0, z_1]$ to $\mathbb{R}$, with $z_0, z_1 \in \mathbb{R}^q$ and $q = dim(z)$. Then, for all $h_1 \geq \max_z\{h(z)\}$ and $h_2 \leq \min_z\{h(z)\}$, there exist two nonnegative functions F_1 and F_2*

$$F_1(z(t)) = \frac{h(z(t)) - h_2}{h_1 - h_2}$$

$$F_2(z(t)) = \frac{h_1 - h(z(t))}{h_1 - h_2}$$

such that:

$$F_1(z(t)) + F_2(z(t)) = 1$$

$$h(z(t)) = F_1(z(t)) \cdot h_1 + F_2(z(t)) \cdot h_2$$

Let us briefly give the important points of the general method to obtain a multi-model structure from a nonlinear formulation, and afterwards illustrate this method by an academical example.

2.1 Analytical Method

Firstly, using a direct factorization of the state x and the input u, the system (1) is transformed into a quasi-linear parameter varying (quasi-LPV) form:

$$\dot{x}(t) = A(x(t), u(t))\, x(t) + B(x(t), u(t))\, u(t) \tag{4a}$$

$$y(t) = C(x(t), u(t))\, x(t) + D(x(t), u(t))\, u(t) \tag{4b}$$

This form is a state and control pseudo-affine representation.

Secondly, the nonlinear entries of the matrices A, B, C and/or D in the variables x and u are considered as "premise variables" and denoted $z_j(x, u)$ ($j = 1, \ldots, q$). Several choices of these premise variables are possible due to the existence of different quasi-LPV forms [for details on the selection procedure see Nagy et al. (2010)]. To each quasi-LPV form, a premise variable set corresponds.

Thirdly, a convex polytopic transformation is performed for all the premise variables ($j = 1, \ldots, q$); thus the premise variables will be split into two parts, as follows:

$$z_j(x, u) = F_{j,1}(z_j(x, u))\, z_{j,1} + F_{j,2}(z_j(x, u))\, z_{j,2} \tag{5}$$

where the scalars $z_{j,1}$, $z_{j,2}$ are defined by

$$z_{j,1} = \max_{x,u} \left\{ z_j(x, u) \right\} \tag{6a}$$

$$z_{j,2} = \min_{x,u} \left\{ z_j(x, u) \right\} \tag{6b}$$

and where the partition functions $F_{j,1}(z_j)$, $F_{j,2}(z_j)$ involved in (5) are:

$$F_{j,1}(z_j(x, u)) = \frac{z_j(x, u) - z_{j,2}}{z_{j,1} - z_{j,2}} \tag{7a}$$

$$F_{j,2}(z_j(x, u)) = \frac{z_{j,1} - z_j(x, u)}{z_{j,1} - z_{j,2}} \tag{7b}$$

Remark 1. For q premise variables, $r = 2^q$ submodels will be obtained.

The two partitions will contribute to the construction of submodels and to the corresponding weighting functions. Then, the weighting functions are defined by some products of the original functions F_{j,σ_i^j}, according to:

$$\mu_i(x, u) = \prod_{j=1}^{q} F_{j,\sigma_i^j}(z_j(x, u)) \tag{8}$$

Considering definition (7a)–(7b), the reader should remark that these functions respect the conditions (3). In definition (8), the indexes σ_i^j ($i = 1, \ldots, 2^q$ and $j = 1, \ldots, q$) are equal to 1 or 2 and indicates which partition of the jth premise variable ($F_{j,1}$ or $F_{j,2}$) is involved in the ith submodel.

The constant matrices A_i ($i = 1, \ldots, 2^q$) are obtained by replacing the premise variables z_j in the matrix A with the scalars defined in (6a)–(6b):

$$A_i = A(z_{1,\sigma_i^1}, \ldots, z_{q,\sigma_i^q}) \tag{9}$$

The form (2) is obtained by similarly defining the matrices B_i, C_i and D_i.

The multi-model is consequently a convex combination of linear submodels, the nonlinearity of the initial system being transferred into the weighting functions related to each sub-model.

2.2 Academical Example

Let us consider the following nonlinear system:

$$\dot{x}_1 = \cos(x_1)x_2 + x_1^3 u \tag{10a}$$

$$\dot{x}_2 = \frac{1}{\sqrt{x_2}}x_1 + x_1^2 x_2 \tag{10b}$$

Firstly, the system (10) can be represented in a quasi-LPV form:

$$\dot{x} = A(x, u)\ x + B(x, u)\ u$$

Several state- and control-affine quasi-LPV forms can be obtained: for the first state equation (10a), this separation is clear because of the product between the function $cos(x_1)$ and the second state variable x_2. For the second term, $x_1^3 u$, we can either affect the nonlinearity x_1^3 in the control matrix B (11), or distribute this nonlinearity among the state vector (x_1 component) and the state matrix A (12):

$$A(x) = \begin{bmatrix} 0 & \cos(x_1) \\ \frac{1}{\sqrt{x_2}} & x_1^2 \end{bmatrix} \qquad B(x) = \begin{bmatrix} x_1^3 \\ 0 \end{bmatrix} \tag{11}$$

$$A(x, u) = \begin{bmatrix} x_1^2 u & \cos(x_1) \\ \frac{1}{\sqrt{x_2}} & x_1^2 \end{bmatrix} \qquad B(x) = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{12}$$

For the second state equation (10b), at least two possible decompositions are observed. The most obvious decomposition is obtained by factorizing the two terms by x_1 and x_2 respectively (11). Another possibility is to factorize the right hand terms of (10b) only by x_1, reducing in this way the number of premise variables to three (13).

$$A(x) = \begin{bmatrix} 0 & \cos(x_1) \\ \frac{1}{\sqrt{x_2}} + x_1 x_2 & 0 \end{bmatrix} \qquad B(x) = \begin{bmatrix} x_1^3 \\ 0 \end{bmatrix} \tag{13}$$

In the following we only focus on the derivation of the MM form. The choice criteria between the possible forms (11)–(13) will be discussed later.

Considering (13), the premise variables linked to the chosen quasi-LPV form are:

$$\begin{aligned} z_1(x) &= \cos(x_1) \\ z_2(x) &= x_1^3 \\ z_3(x) &= \tfrac{1}{\sqrt{x_2}} + x_1 x_2 \end{aligned} \tag{14}$$

Secondly, the convex polytopic transformation is applied, for each premise variable $z_j(x)$ ($j = 1, \ldots, 3$) for $x_1 \in [-2\pi, 2\pi]$ and $x_2 \in [0.1, 12]$. Then, using Lemma 1, each premise variable will be partitioned into two parts:

$$z_1(x) = F_{1,1}(z_1) \cdot z_{1,1} + F_{1,2}(z_1) \cdot z_{1,2} \tag{15a}$$

$$z_2(x) = F_{2,1}(z_2) \cdot z_{2,1} + F_{2,2}(z_2) \cdot z_{2,2} \tag{15b}$$

$$z_3(x) = F_{3,1}(z_3) \cdot z_{3,1} + F_{3,2}(z_3) \cdot z_{3,2} \tag{15c}$$

where $F_{j,1}(z_j(x))$ and $F_{j,2}(z_j(x))$ are defined using Lemma 1. For example:

$$F_{1,1}(z_1(x)) = \frac{\cos(x_1) - z_{1,2}}{z_{1,1} - z_{1,2}} \tag{16}$$

and so on. The bounds $z_{j,1}$ and $z_{j,2}$ are chosen as in (6). The functions $F_{j,1}$ and $F_{j,2}$ respectively represent the first and the second partition of each premise variable. Let us note that $A(x)$ involves z_1 and z_3 as premise variables, while z_2 is involved in $B(x)$. Then, the matrices A and B will be evaluated at the vertices of the polytopes defined by the partitions of the premise variables involved in these matrices.

Applying the convex polytopic transformation (Lemma 1) to z_1 (15a), it follows:

$$A(z_1, z_3) = \begin{bmatrix} 0 & z_1(x) \\ z_3(x) & 0 \end{bmatrix} = F_{1,1}(x) \begin{bmatrix} 0 & z_{1,1} \\ z_3(x) & 0 \end{bmatrix} + F_{1,2}(x) \begin{bmatrix} 0 & z_{1,2} \\ z_3(x) & 0 \end{bmatrix}$$

Applying the convex polytopic transformation (Lemma 1) to z_3 (15c), it follows:

$$\begin{aligned} A(z_1, z_3) = F_{1,1}F_{3,1}(x) \begin{bmatrix} 0 & z_{1,1} \\ z_{3,1} & 0 \end{bmatrix} + F_{1,2}F_{3,1}(x) \begin{bmatrix} 0 & z_{1,2} \\ z_{3,1} & 0 \end{bmatrix} \\ + F_{1,1}F_{3,2}(x) \begin{bmatrix} 0 & z_{1,1} \\ z_{3,2} & 0 \end{bmatrix} + F_{1,2}F_{3,2}(x) \begin{bmatrix} 0 & z_{1,1} \\ z_{3,2} & 0 \end{bmatrix} \end{aligned}$$

As indicated in (2), the same weighting functions have to multiply the matrices A, B and C. In order to also include the partitions of the premise variable z_2, involved in $B(z_2)$ but not in $A(z_1, z_3)$, the matrix A is multiplied by $F_{2,1}(x) + F_{2,2}(x) = 1$:

$$
\begin{aligned}
A(z_1,z_3) = \; & F_{1,1}(x)F_{2,1}(x)F_{3,1}(x)\begin{bmatrix} 0 & z_{1,1} \\ z_{3,1} & 0 \end{bmatrix} + F_{1,2}(x)F_{2,1}(x)F_{3,1}(x)\begin{bmatrix} 0 & z_{1,2} \\ z_{3,1} & 0 \end{bmatrix} \\
& + F_{1,1}(x)F_{2,2}(x)F_{3,1}(x)\begin{bmatrix} 0 & z_{1,1} \\ z_{3,1} & 0 \end{bmatrix} + F_{1,2}(x)F_{2,2}(x)F_{3,1}(x)\begin{bmatrix} 0 & z_{1,2} \\ z_{3,1} & 0 \end{bmatrix} \\
& + F_{1,1}(x)F_{2,1}(x)F_{3,2}(x)\begin{bmatrix} 0 & z_{1,1} \\ z_{3,2} & 0 \end{bmatrix} + F_{1,2}(x)F_{2,1}(x)F_{3,2}(x)\begin{bmatrix} 0 & z_{1,2} \\ z_{3,2} & 0 \end{bmatrix} \\
& + F_{1,1}(x)F_{2,2}(x)F_{3,2}(x)\begin{bmatrix} 0 & z_{1,1} \\ z_{3,2} & 0 \end{bmatrix} + F_{1,2}(x)F_{2,2}(x)F_{3,2}(x)\begin{bmatrix} 0 & z_{1,2} \\ z_{3,2} & 0 \end{bmatrix}
\end{aligned} \tag{17}
$$

The same transformations are performed on the matrix $B(z_2)$:

$$
\begin{aligned}
B(z_2) &= \begin{bmatrix} z_2(x) \\ 0 \end{bmatrix} = \begin{bmatrix} z_{2,1}F_{2,1}(x) + z_{2,2}F_{2,2}(x) \\ 0 \end{bmatrix} = F_{2,1}(x)\begin{bmatrix} z_{2,1} \\ 0 \end{bmatrix} + F_{2,2}(x)\begin{bmatrix} z_{2,2} \\ 0 \end{bmatrix} \\
&= [F_{1,1}(x) + F_{1,2}(x)]\,[F_{3,1}(x) + F_{3,2}(x)]\left\{F_{2,1}(x)\begin{bmatrix} z_{2,1} \\ 0 \end{bmatrix} + F_{2,2}(x)\begin{bmatrix} z_{2,2} \\ 0 \end{bmatrix}\right\}
\end{aligned} \tag{18}
$$

Finally, from (17) and (18) one obtains:

$$
A(z_1,z_3) = \sum_{i=1}^{8} \mu_i(x)A_i, \qquad B(z_2) = \sum_{i=1}^{8} \mu_i(x)B_i \tag{19}
$$

where $\mu_i(x)$ are combination of $F_{j,k}(x)$ ($j = 1,2,3$ and $k = 1,2$) and where

$$
\begin{aligned}
A_1 = A_3 &= \begin{bmatrix} 0 & z_{1,1} \\ z_{3,1} & 0 \end{bmatrix} & A_2 = A_4 &= \begin{bmatrix} 0 & z_{1,1} \\ z_{3,2} & 0 \end{bmatrix} \\
A_5 = A_7 &= \begin{bmatrix} 0 & z_{1,2} \\ z_{3,1} & 0 \end{bmatrix} & A_6 = A_8 &= \begin{bmatrix} 0 & z_{1,2} \\ z_{3,2} & 0 \end{bmatrix} \\
B_1 = B_2 = B_5 = B_6 &= \begin{bmatrix} z_{2,1} \\ 0 \end{bmatrix} & B_3 = B_4 = B_7 = B_8 &= \begin{bmatrix} z_{2,2} \\ 0 \end{bmatrix}
\end{aligned} \tag{20}
$$

After this example it is interesting to present a systematic way of constructing the matrices A_i and B_i. For example, to determine A_3 and B_3, the triplet $\sigma_3 = (1,2,1)$ is used. This triplet codes the variable partitions occurring in the 3rd submodel and σ_3^k denotes the kth value in the triplet σ_3. According to the expression of A_3 and B_3, these matrices may be denoted: $A_3 = A(z_{1,\sigma_3^1}, z_{3,\sigma_3^3})$ and $B_3 = B(z_{2,\sigma_3^2})$, where z_{1,σ_3^1}, z_{2,σ_3^2} and z_{3,σ_3^3} are the scalars defined in (6). In a more general way, A_i and B_i ($i = 1,\ldots,8$) are denoted:

$$
\begin{aligned}
A_i &= A(z_{1,\sigma_i^1}, z_{3,\sigma_i^3}) \\
B_i &= B(z_{2,\sigma_i^2})
\end{aligned}
$$

Those notations are consistent with (20). Associated to A_3 and B_3, the definition of (19) is obtained by using the triplet σ_3. Indeed:

$$\mu_3(x) = F_{1,\sigma_3^1}(x) F_{2,\sigma_3^2}(x) F_{3,\sigma_3^3}(x) \tag{21}$$

Each function defining a premise variable being partitioned into two functions, there are 2^3 submodels and 2^3 weighting functions. To each submodel i corresponds a triplet σ_i which codes the variable partitions occurring in it. After multiplying the functions representing these partitions, the weighting function $\mu_i(x)$ corresponding to the ith submodel is obtained.

To express the constant matrices A_i and B_i, characterizing each submodel i ($i = 1, \dots, 8$), we use the quasi-LPV form (13) of the system (10), where $A(x, u)$ and $B(x, u)$ were defined in (13).

2.3 Choice Criteria for Quasi-LPV Form

Most of the existing results concerning performance analysis or observer/controller design for MM systems are based on the solution of linear matrix inequalities (LMI) obtained by using the Lyapunov method. Because of the convex sum property of the weighting functions, the LMI are only evaluated at the polytope vertices (A_i, B_i, C_i, D_i) and the weighting functions do not occur in the resolution of the LMIs (Tanaka et al. 2001; Wang et al. 1996). Only the matrices A_i, B_i, C_i and D_i are involved in the LMIs. Moreover, it should be highlighted that the LMI formulation generally results in sufficient conditions, since only the convex sum properties of the weighting functions are used. As a consequence, even if all the quasi-LPV models are exact equivalent rewritings of the original nonlinear system, the analysis or design results (obtained from an LMI procedure) may not be identical for all the possible MM forms that can be built from a given nonlinear system. That is why the choice of the premise variable set and the corresponding submodels is a critical point in the MM form derivation and it is essential to propose choice criteria for the MM structure (Nagy et al. 2010; Nagy 2010a) in order to obtain the most suitable MM form and thus reduce the complexity of a nonlinear system.

First of all, in the framework of controller/observer design, the controllability/observability of the system under MM form should be ensured. A necessary—but not sufficient—condition for LMI-based designs is that all the submodels are controllable/observable, thus, the quasi-LPV forms producing submodels that are not controllable/observable must be eliminated. For instance, in the previous example, the form (12) with $B_i = 0$, is not suitable for controller design since all the submodels are uncontrollable.

The number of LMI constraints used for analysis and design is directly linked to the number of submodels: it is linear or polynomial in r (Tanaka et al. 2001). Obviously, the larger this number of LMI constraints is, the less likely a solution to the LMI optimization exists. Also from a computational point of view, it is thus useful to chose the quasi-LPV form with a minimal r, that is to say with a minimum number of premise variables.

In addition to that, the observer/controller design for MM with premise variables depending on the state variables is a lot more complex than if the premise variables are known (Ichalal et al. 2009, 2010; Nagy-Kiss et al. 2011; Yoneyama 2009). As a consequence, MM form with premise variables depending on a minimal number of state variables is preferable.

2.4 Multiple Time Scale Case

Real systems can have multiple time scale dynamics. In this case, the singular perturbation theory is often used to systematically identify the different time scales and to decompose the system dynamics according to them (Kumar et al. 1998; O'Malley and Robert 1991). Nevertheless, it is generally not trivial to model a process under the standard singularly perturbed form. One of the main tasks to realize is the identification and separation of the so-called slow and fast dynamics. In Dong et al. (2007) this identification/separation is realized for a particular biological process by comparing its kinetic parameters. But this approach is dedicated to biological processes that are far from encompassing all nonlinear systems. So, more general methods to identify different time scales were proposed in Robert (1992). These methods are based on the evaluation of the jacobian eigenvalues of the linearized system and will be used here.

After the separation of the multiple-time scale dynamics, the standard singularly perturbed form is obtained. In the limit case, when the singular perturbed parameter tends towards zero, a reduced form can be derived, with a dynamic part expressed by ordinary differential equations and a static part expressed by analytic equations, allowing to reduce the complexity of the model and simplifying its use, for control, estimation and diagnosis.

2.4.1 The Singularly Perturbed Form

The standard formulation of the singular perturbed systems with two-time scales and unknown inputs (UI) can be expressed as follows:

$$\epsilon \dot{x}_f(t) = f_f(x_s(t), x_f(t), u(t), d(t), \theta(t), \epsilon) \tag{22a}$$

$$\dot{x}_s(t) = f_s(x_s(t), x_f(t), u(t), d(t), \theta(t), \epsilon) \tag{22b}$$

$$y(t) = g(x(t), u(t), d(t)) \tag{22c}$$

where $x = [x_f, \ x_s]^T$, $x_s \in \mathbb{R}^{n_s}$ and $x_f \in \mathbb{R}^{n_f}$ are respectively the slow and fast state variables, $u \in \mathbb{R}^{n_u}$ the input vector, $d \in \mathbb{R}^{n_d}$ the unknown input vector, $\theta \in \mathbb{R}^{n_\theta}$ the modeling uncertainty, $y \in \mathbb{R}^{n_y}$ the output vector, $f_f \in \mathbb{R}^{n_f}$, $f_s \in \mathbb{R}^{n_s}$, $g \in \mathbb{R}^{n_y}$ and ϵ is a small and positive scalar, known as *singular perturbed parameter*.

Model uncertainty $\theta(t)$ generally refers to a difference between the model and the real system. It can be caused by imperfect knowledge or changes of the process or of its operating conditions. It can also be due to malfunctions acting on the process parameters. The unknown inputs $d(t)$ allow to model external disturbances or unmeasured inputs of the system. The nonlinear dynamic model with two time scales (22) takes these internal and external uncertainties into account.

In the limit case where $\epsilon \to 0$, the degree of the system (22) degenerates from $n_f + n_s$ to n_s, and the system is approximated by the following reduced system:

$$\begin{aligned}\bar{E}\dot{x}(t) &= \begin{bmatrix} f_f(x_f(t), x_s(t), u(t), d(t), \theta(t), 0) \\ f_s(x_f(t), x_s(t), u(t), d(t), \theta(t), 0) \end{bmatrix} \\ &= f(x(t), u(t), d(t), \theta(t)) \qquad (23a) \\ y(t) &= g(x(t), u(t), d(t)) \qquad (23b)\end{aligned}$$

with $\bar{E}$ defined by:

$$\bar{E} = \begin{bmatrix} 0_{n_f} & 0 \\ 0 & I_{n_s} \end{bmatrix} \qquad (24)$$

In order to obtain the standard singularly perturbed form (23) from a classical nonlinear modeling (1), the identification and separation of slow and fast dynamics is the key point (Dong et al. 2007; Steffens et al. 1997). The mathematical homotopy method for the linearized system, proposed by Wasynczuk and Decarlo (1981) and later improved by Robert (1992), is used to link each state variable with an eigenvalue. By comparing the eigenvalues, the biggest (respectively the smallest) ones will be associated with the slowest (respectively fastest) dynamics. Note that the linearized system is only used to identify the slow and fast dynamics, but not for the observer design. An equivalent MM representation will be used for this purpose, as presented in the previous Sect. 2.1.

2.4.2 The Homotopy Method

Based on the eigenvalue analysis of the linearized system, the homotopy method allows the identification and separation of the slow and fast dynamics (Robert 1992).

Let us consider the linearization of the nonlinear system (1) around various equilibrium points (x_0, u_0):

$$\dot{x}(t) = A_0 x(t) + B_0 u(t) \qquad (25)$$

where $A_0 = \dfrac{\partial f(x,u)}{\partial x}\Big|_{(x_0,u_0)}$ and $B_0 = \dfrac{\partial f(x,u)}{\partial u}\Big|_{(x_0,u_0)}$.

Ordering the eigenvalues of A_0 according to $\lambda_1 \leq \lambda_2 \leq \ldots \leq \lambda_{n_x}$, the biggest (resp. smallest) eigenvalue corresponds to the slowest (resp. fastest) dynamic. The separation is performed by fixing a threshold τ, such that: $\lambda_1 \leq \ldots \leq \lambda_{n_f} << \tau \leq \lambda_{n_f+1} \leq \ldots \leq \lambda_n$.

If every eigenvalue can be connected to a given state variable, thus the dynamics of every state can be quantitatively estimated. The homotopy method requires to consider a system such that there exists an obvious relation between the eigenvalues and the states, as for example the diagonalized matrix of the jacobian matrix A_0. Further details on this method will be given in Sect. 4 with the application to the WWTP.

2.4.3 Singular Multi-models

A singular MM can be derived from a nonlinear singular systems in a similar way than the MM has been obtained from the nonlinear systems (1) in Sect. 2. The singularly perturbed systems presented under a MM form with unknown inputs and modeling uncertainty has the following form:

$$\bar{E}\,\dot{x}(t) = \sum_{i=1}^{r} \mu_i(x(t), u(t))\,[A_i(\theta(t))x(t) + B_i(\theta(t))u(t) + E_i d(t)] \tag{26a}$$

$$y(t) = Cx(t) + Du(t) + Gd(t) \tag{26b}$$

where the weighting functions $\mu_i(x, u)$ depend on the unmeasurable state variables $x \in \mathbb{R}^{n_x}$ and on the input variables $u \in \mathbb{R}^{n_u}$. The variables $d \in \mathbb{R}^{n_d}$ are the unknown inputs, $\theta(t) \in \mathbb{R}^{n_\theta}$ the modeling uncertainty and $y \in \mathbb{R}^{n_y}$ the output variables. The matrices E_i, C, D and G are known real matrices and $A_i(\theta(t))$, $B_i(\theta(t))$ are time varying matrices. The matrix $\bar{E}$ can be a singular matrix (i.e. $rank(\bar{E}) \leq n_x$). The functions $\mu_i(x, u)$ respect the convexity conditions. Since in most practical situations, the sensor location and characteristics do not depend on the operating conditions, it is realistic to consider linear time invariant output equation (26b). This assumption is satisfied by the WWTP considered as an application in this chapter.

2.5 Modeling Uncertainties as Unknown Inputs in the MM

In most studies (Nagy-Kiss et al. 2012; Yoneyama 2009; Zamani and Zarif 2011) the modeling uncertainties are norm bounded and are expressed additively in the state matrix of the dynamic nonlinear model (Nagy-Kiss et al. 2012). In this chapter, more general class of modeling uncertainties is assumed.

Let us consider that the uncertainties $\theta(t) = \left[\theta_1(t), \theta_2(t), \cdots \theta_{n_\theta}(t)\right]^T$ occur linearly in A_i and B_i (26):

$$A_i(\theta(t)) = A_{i,0} + \sum_{j \in I_A} \theta_j(t) A_{i,j}, \quad B_i(\theta(t)) = B_{i,0} + \sum_{j \in I_B} \theta_j(t) B_{i,j} \tag{27}$$

The components $\theta_j(t)$ of the vector $\theta(t)$ are time-varying parameters. The index set I_A, with $n_A = card(I_A)$, (resp. I_B, with $n_B = card(I_B)$) gathers the indexes of the components of the vector $\theta(t)$ that are involved in the matrices $A_i(\theta(t))$ (resp. $B_i(\theta(t))$). Obviously, these sets satisfy the following property: $I_A \cup I_B = I_\theta$, where $I_\theta = \{1, \ldots, n_\theta\}$. Moreover, $\theta_j^A(t)$, for $j = 1, \ldots, n_A$ (resp. $\theta_j^B(t)$, for $j = 1, \ldots, n_B$) denote the components of $\theta(t)$ involved in $A_i(\theta(t))$ (resp. $B_i(\theta(t))$). The matrices $A_{i,0}, B_{i,0}, A_{i,j}$ ($i = 1, \cdots, r$ and $j \in I_A$) and $B_{i,j}$ ($i = 1, \cdots, r$ and $j \in I_B$) are constants known matrices.

These uncertainties cause changes in the model parameters and may impact on the system stability. They are called multiplicative faults since they appear as product terms in (26). The main goal in the state estimation framework, is to minimize the influence of these parameter changes on the state estimation error. To this aim, these time-varying parameters can be considered as unknown inputs, by augmenting $d(t)$. Substituting the uncertain matrices (27) in (26) yields to:

$$\begin{aligned} \bar{E}\dot{x}(t) &= \sum_{i=1}^{r} \mu_i(z(t)) \left[\left(A_{i,0} + \sum_{j \in I_A} \theta_j(t) A_{i,j} \right) x(t) \right. \\ &\quad \left. + \left(B_{i,0} + \sum_{j \in I_B} \theta_j(t) B_{i,j} \right) u(t) + E_i d(t) \right] \\ y(t) &= Cx(t) + Du(t) + Gd(t) \end{aligned} \tag{28}$$

Defining the augmented UI and its incidence matrices by:

$$\begin{aligned} \bar{d}(t) &= \left[(\theta_1^A(t)x(t))^T \ldots (\theta_{n_A}^A(t)x(t))^T \; (\theta_1^B(t)u(t))^T \ldots (\theta_{n_B}^B(t)u(t))^T \; d^T(t) \right]^T \\ \bar{F}_i &= \left[A_{i,1} \ldots A_{i,n_A} \; B_{i,1} \ldots B_{i,n_B} \; E_i \right] \\ \bar{G} &= \left[0 \ldots 0 \; 0 \ldots 0 \; G \right] \end{aligned}$$

the uncertain MM with UI can be written as the following MM (with an augmented UI but no uncertain terms):

$$\begin{aligned} \bar{E}\dot{x}(t) &= \sum_{i=1}^{r} \mu_i(x(t), u(t)) \left[A_{i,0}x(t) + B_{i,0}u(t) + \bar{F}_i \bar{d}(t) \right] \\ y(t) &= Cx(t) + Du(t) + \bar{G}\bar{d}(t) \end{aligned} \tag{29}$$

3 Observer Synthesis for Singular Multi-models

As seen in the previous section, the singular MM approach is a powerful tool to represent two time scale nonlinear systems, at least on a compact set of the state space (Chap. 14 of Tanaka et al. 2001, Nagy et al. 2010). It should be highlighted that although the CPT naturally leads to MM with premise variables depending on the state variable, and thus being unmeasurable, most of the existing works on MM consider measured premise variables. Only a few works are devoted to MM with unmeasurable premise variables (UPV) depending on the state variables (Bezzaoucha et al. 2013; Ichalal et al. 2009; Nagy-Kiss et al. 2011, 2015). Since state estimation is known to be a crucial step in process control or diagnosis, thus observer design for singular MM affected by unknown input (UI) with UPV is of interest.

On the one hand, some works are devoted to state estimation of nonsingular MM with UPV (Bergsten et al. 2002; Ichalal et al. 2010; Yoneyama 2009), which is not trivial since the weighting functions used to synthesize the observer cannot depend on the state variables and will involve their estimates. On the other hand, many works deal with observer design for singular systems (see the book Xu and Lam 2006 and the references therein) and some of them are dedicated to state estimation of singular MM with UI (Marx et al. 2007), but the premise variables are supposed to be measured.

Here an unknown input observer (UIO) for descriptor MM with UPV is proposed. The proposed observer is a nonsingular MM in order to simplify the implementation. The existence conditions of the observer are expressed through linear matrix inequalities (LMI) by using the Lyapunov method and the $\mathcal{L}_2$ approach. The LMI approach has been chosen since it is well known to be a convenient tool to formulate various design objectives (stability, norm-bound, etc.) (Boyd et al. 1994). In the following, the system under consideration is a singularly perturbed nonlinear system with two time scales (23), rewritten as a singular MM with UI and UPV (29).

Hypothesis 3.1 *The model* (29) *satisfies the following rank condition*

$$rank(W) = rank\left(\begin{bmatrix} W \\ Y \end{bmatrix}\right) \tag{30}$$

where, denoting the Kronecker product by $\otimes$, *W and Y are defined by:*

$$W = \left[\begin{array}{cc|ccc} \bar{E} & 0_{n_x \times n_d} & \bar{F}_1 & \cdots & \bar{F}_r \\ C & \bar{G} & 0_{n_y \times n_d} & \cdots & 0_{n_y \times n_d} \\ \hline 0_{rn_y \times n_x} & 0_{rn_y \times n_d} & & I_r \otimes \bar{G} & \end{array}\right] \tag{31a}$$

$$Y = \left[\begin{array}{cc|c} I_{n_x} & 0_{n_x \times n_d} & 0_{n_x \times rn_d} \end{array}\right] \tag{31b}$$

In order to simplify its implementation, the proposed following observer is chosen to be a nonsingular MM, even if the system to estimate is singular:

$$\dot{\xi}(t) = \sum_{i=1}^{r} \mu_i(\hat{x}, u)\,[N_i\xi(t) + G_i u(t) + L_i y(t)] \tag{32}$$

$$\hat{x}(t) = \xi(t) + T_2 y(t) - T_2 D u(t) \tag{33}$$

where $\hat{x}(t)$ denotes the state estimate. The state estimation error is given by

$$e(t) = x(t) - \hat{x}(t) \tag{34}$$

It is important to note that the weighting functions μ involved in the observer (32) depends on the $\hat{x}$ and thus the observer is nonlinear.

The observer design reduces to finding the gains N_i, G_i, L_i and T_2 such that the state estimation error obey to a stable generating system.

Theorem 1. *The observer (32) for the system (26) is obtained by finding a symmetric and positive definite matrix $X \in \mathbb{R}^{n_x \times n_x}$ and a matrix $\tilde{Z} \in \mathbb{R}^{n_x \times (n_x + n_y(r+1))}$ that minimize the positive scalar $\bar{\gamma}$ under the following LMI constraints:*

$$\begin{bmatrix} \Phi_i & (X\,Y\,W^+ + \tilde{Z}\,W^\perp)\,\Omega \\ \Omega^T\,(X\,Y\,W^+ + \tilde{Z}\,W^\perp)^T & -\bar{\gamma} I \end{bmatrix} < 0 \qquad i = 1, \ldots, r \tag{35}$$

where the matrices Ω and Φ_i are defined by

$$\Omega = [\, I_n \quad 0 \mid 0 \quad \cdots \quad 0\,]^T$$

$$\Phi_i = (YW^+Y_i)^T X + X\,(Y\,W^+\,Y_i) + (W^\perp Y_i)^T \tilde{Z}^T + \tilde{Z}\,(W^\perp Y_i) + I \tag{36}$$

with $W \in \mathbb{R}^{(n_x+n_y(r+1))\times(n_x+n_d(r+1))}$ and $Y \in \mathbb{R}^{n_x \times (n_x+n_d(r+1))}$ are defined by (31), and where W^+ is the pseudo inverse of W, $W^\perp = I - WW^+$ denotes the orthogonal of W verifying $W^\perp W = 0$ and where the matrices $Y_i \in \mathbb{R}^{(n_x+n_y(r+1))\times n_x}$ are defined by

$$Y_i = \begin{bmatrix} A_{i,0} \\ 0_{l\times n} \\ \hline v_i \otimes C \end{bmatrix}, \quad i = 1, \ldots, r \tag{37}$$

The vector $v_i \in \mathbb{R}^{r\times 1}$ is the column vector containing 1 on the ith entry and 0 on all the others.

Once X and $\tilde{Z}$ are obtained from LMI optimization (35), the matrices Z, T_1, T_2 and K_i ($i = 1, \ldots, r$) can be deduced by

$$Z = X^{-1}\tilde{Z} \tag{38}$$

$$\left[T_1 \; T_2 \,\middle|\, K_1 \; \ldots \; K_r\right] = YW^+ + ZW^\perp \tag{39}$$

Finally, the observer gains are determined by

$$N_i = T_1 A_{i,0} + K_i C \tag{40}$$

$$G_i = T_1 B_{i,0} \tag{41}$$

$$L_i = N_i T_2 - K_i \tag{42}$$

Proof. See Kiss et al. (2011). □

4 Application to Wastewater Treatment Plant

4.1 Process Description and ASM1 Model

The widely used activated sludge wastewater treatment plant consists in mixing used waters with a rich mixture of bacteria in order to degrade the organic matter (Olsson and Newell 1999). In this work, the data are generated by a part of the COST Benchmark (Copp 2002). The chosen WWTP configuration is a single tank (or bioreactor) and a settler (or clarifier), its general structure is depicted on Fig. 1. On Fig. 1, q_{in} represents the wastewater input flow, q_{out} the output flow, q_a the air flow and q_r (resp. q_w) are the recycled (resp. rejected) flow. The reactor volume V is assumed to be constant and thus the following equality is available for the reactor: $q_{out}(t) = q_{in}(t) + q_r(t)$. In general, $q_r(t)$ and $q_w(t)$ represent fractions of the input flow: $q_r(t) = f_r\, q_{in}(t)$, $1 \leq f_r \leq 2$, $q_w(t) = f_w\, q_{in}(t)$, $0 < f_w < 1$.

The polluted water circulates in the bioreactor where the bacterial biomass degrades the organic pollutant. Micro-organisms bring together in flocs and produce sludge, that is sent to the clarifier where the separation of the bacterial biomass from the purified water is made by gravity. A fraction of settled sludges is recycled towards the bioreactor to maintain its capacity of purification.

For observer/controller design, models of lower complexity are required since the full ASM1 model is quite complicated and may contain unnecessary informations

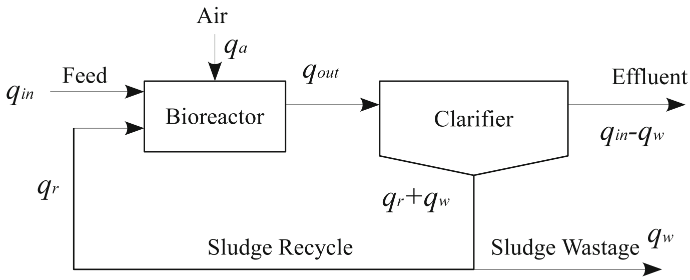

Fig. 1 Wastewater treatment process diagram

for control and diagnosis tasks. Nevertheless, a quite complete model is considered here, since it involves the following components: soluble carbon S_S, particulate X_S, dissolved oxygen S_O, heterotrophic biomass X_{BH}, ammonia S_{NH}, nitrate S_{NO}, autotrophic biomass X_{BA}, soluble inert S_I, suspended inert X_I, soluble organic nitrogen S_{ND} and suspended organic nitrogen X_{ND}. Only the following components are not considered: the inert component X_P and the alkalinity S_{alk}. In practical situation, a single organic compound (denoted X_{DCO}) will be considered by adding the soluble part S_S and the particulate part X_S (Smets et al. 2003).

According to the setup of the European Benchmark COST 624 (Copp 2002), it is assumed that $S_{O,in} \cong 0$, $S_{NO,in} \cong 0$ and $X_{BA,in} \cong 0$. Here, the operating conditions of the Bleesbrück (Luxembourg) WWTP are used for modeling and simulation: the concentrations $S_{NH,in}$, $X_{DCO,in}$ and $X_{BH,in}$ are not measured on line. Thus, $S_{NH,in}$ is considered as an unknown input and a daily mean value is used for $X_{DCO,in}$ and $X_{BH,in}$, which is a frequently used approximation. The measured concentrations are: the dissolved oxygen S_O, routinely measured in activated sludge WWTP, both nitrate S_{NO} and ammonia S_{NH} and the organic compound X_{DCO}. Consequently, the output $y = y(t)$, the input $u = u(t)$ and the unknown input $d = d(t)$ vectors are:

$$y = [X_{DCO},\ \ S_O,\ \ S_{NH},\ \ S_{NO}]^T \tag{43}$$

$$u = [X_{DCO,in},\ q_a,\ X_{BH,in}, S_{I,in},\ X_{I,in},\ S_{ND,in},\ X_{ND,in}]^T \tag{44}$$

$$d = S_{NH,in} \tag{45}$$

Let us consider the following explicit form of the ASM1:

$$\begin{aligned}
\dot{X}_{DCO}(t) &= -\frac{1}{Y_h}[\varphi_1(t) + \varphi_2(t)] + (1 - f_p)(\varphi_4(t) + \varphi_5(t)) + D_1(t) \\
\dot{S}_O(t) &= \frac{Y_h - 1}{Y_h}\varphi_1(t) + \frac{Y_a - 4.57}{Y_a}\varphi_3(t) + D_2(t) \\
\dot{S}_{NH}(t) &= -i_{xb}[\varphi_1(t) + \varphi_2(t)] - \left[i_{xb} + \frac{1}{Y_a}\right]\varphi_3(t) + D_3(t) \\
&\quad + (i_{xb} - f_p\, i_{xp})[\varphi_4(t) + \varphi_5(t)] \\
\dot{S}_{NO}(t) &= \frac{Y_h - 1}{2.86 Y_h}\varphi_2(t) + \frac{1}{Y_a}\varphi_3(t) + D_4(t) \\
\dot{X}_{BH}(t) &= \varphi_1(t) + \varphi_2(t) - \varphi_4(t) + D_5(t) \\
\dot{X}_{BA}(t) &= \varphi_3(t) - \varphi_5(t) + D_6(t) \\
\dot{S}_I(t) &= D_7(t) \\
\dot{X}_I(t) &= f_p[\varphi_4(t) + \varphi_5(t)] + D_8(t) \\
\dot{S}_{ND}(t) &= -\varphi_6(t) + \varphi_8(t) + D_9(t) \\
\dot{X}_{ND}(t) &= (i_{xb} - f_p i_{xp})[\varphi_4(t) + \varphi_5(t)] - \varphi_8(t) + D_{10}(t)
\end{aligned} \tag{46}$$

where

$$
\begin{array}{rcl}
\varphi_1(t) & = & \mu_h \frac{X_{DCO}(t)}{K_{dco}+X_{DCO}(t)} \frac{S_O(t)}{K_{oh}+S_O(t)} X_{BH}(t) \\
\varphi_2(t) & = & \mu_h \eta_{NOg} \frac{X_{DCO}(t)}{K_{dco}+X_{DCO}(t)} \frac{S_{NO}(t)}{K_{no}+S_{NO}(t)} \frac{K_{oh}}{K_{oh}+S_O(t)} X_{BH}(t) \\
\varphi_3(t) & = & \mu_a \frac{S_{NH}(t)}{K_{nh,a}+S_{NH}(t)} \frac{S_O(t)}{K_{o,a}+S_O(t)} X_{BA}(t) \\
\varphi_4(t) & = & b_h X_{BH}(t) \\
\varphi_5(t) & = & b_a X_{BA}(t) \\
\varphi_6(t) & = & k_a S_{ND}(t) X_{BH}(t) \\
\varphi_7(t) & = & k_h \frac{X_{DCO}(t)/X_{BH}(t)}{K_{dco}+X_{DCO}(t)/X_{BH}(t)} \left(\frac{S_O(t)}{K_{oh}+S_O(t)} + \eta_h \frac{K_{oh}}{K_{oh}+S_O(t)} \frac{S_{NO}(t)}{K_{no}+S_{NO}(t)} \right) X_{BH}(t) \\
\varphi_8(t) & = & k_h \frac{X_{ND}(t)/X_{BH}(t)}{K_{dco}+X_{DCO}(t)/X_{BH}(t)} \left(\frac{S_O(t)}{K_{oh}+S_O(t)} + \eta_h \frac{K_{oh}}{K_{oh}+S_O(t)} \frac{S_{NO}(t)}{K_{no}+S_{NO}(t)} \right) X_{BH}(t)
\end{array}
$$

and where Y_a, Y_h, f_p, i_{xb}, i_{xp} are constant coefficients and $K_{dco} = \frac{K_s}{f_{ss}}$.

The input/output balance is defined by:

$$
\begin{array}{rcl}
D_1(t) & = & D_{in}(t)\,[X_{DCO,in}(t) - X_{DCO}(t)] \\
D_2(t) & = & D_{in}(t)\,[-S_O(t)] + Kq_a(t)\,[S_{O,sat} - S_O(t)] \\
D_3(t) & = & D_{in}(t)\,[S_{NH,in}(t) - S_{NH}(t)] \\
D_4(t) & = & D_{in}(t)\,[-S_{NO}(t)] \\
D_5(t) & = & D_{in}(t) \left[X_{BH,in}(t) - X_{BH}(t) + \frac{f_r(1-f_w)}{f_r+f_w} X_{BH}(t) \right] \\
D_6(t) & = & D_{in}(t) \left[-X_{BA}(t) + \frac{f_r(1-f_w)}{f_r+f_w} X_{BA}(t) \right] \\
D_7(t) & = & D_{in}(t)[S_{I,in}(t) - S_I(t)] \\
D_8(t) & = & D_{in}(t) \left[X_{I,in}(t) - X_I(t) + \frac{f_r(1-f_w)}{f_r+f_w} \right] X_I(t) \\
D_9(t) & = & D_{in}(t)[S_{ND,in}(t) - S_{ND}(t)] \\
D_{10}(t) & = & D_{in}(t) \left[X_{ND,in}(t) - X_{ND}(t) + \frac{f_r(1-f_w)}{f_r+f_w} \right] X_{ND}(t)
\end{array}
\tag{47}
$$

where $D_{in}(t) = \frac{q_{in}(t)}{V}$. For numerical applications, the following heterotrophic growth and decay kinetic parameters are used (Olsson and Newell 1999): $\mu_h = 3.733[1/24\,\text{h}]$, $\mu_a = 0.3[1/24\,\text{h}]$, $K_s = 20[\text{g/m}^3]$, $f_{ss} = 0.79$, $K_{oh} = 0.2[\text{g/m}^3]$, $K_{o,a} = 0.4[\text{g/m}^3]$, $K_{no} = 0.5[\text{g/m}^3]$, $K_{nh,a} = 1[\text{g/m}^3]$, $b_h = 0.3[1/24\,\text{h}]$, $b_a = 0.05[1/24\,\text{h}]$, $\eta_{NOg} = 0.8$. The stoichiometric parameters are $Y_h = 0.6$[g cell formed], $Y_a = 0.24$[g cell formed], $i_{xb} = 0.086$[g N in biomass], $i_{xp} = 0.06$[g N in endogenous mass], $f_p = 0.1$ and the oxygen saturation concentration is $S_{O,sat} = 10[\text{g/m}^3]$, $f_r = 1.1$ and $f_w = 0.04$, $V = 1333[\text{m}^3]$.

4.2 Slow and Fast Variable Separation

In this section the identification of the slow and fast dynamics of the ASM1 model (46) is realized with the homotopy method (Robert 1992), described in

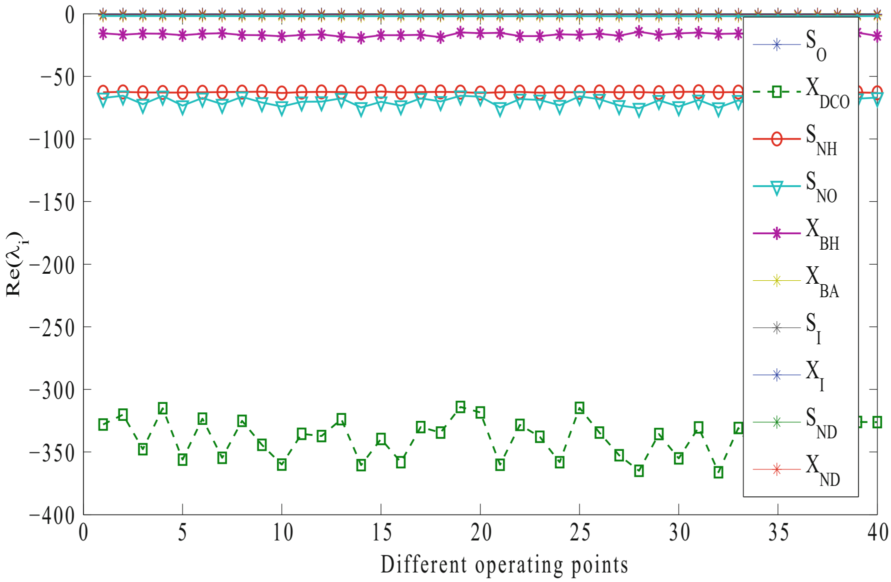

Fig. 2 The eigenvalues of the linearized decoupled system

Sect. 2.4. Let us consider the linearization of the nonlinear system (46) around various equilibrium points (x_0, u_0):

$$\dot{x}(t) = A_0 x(t) + B_0 u(t) \tag{48}$$

where $A_0 = \dfrac{\partial f(x,u)}{\partial x}\Big|_{(x_0,u_0)}$ and $B_0 = \dfrac{\partial f(x,u)}{\partial u}\Big|_{(x_0,u_0)}$.

For the considered model ASM1 (46), the separation of two time scale dynamics is confirmed by the eigenvalues of the jacobian A_0, depicted on Fig. 2 for forty operating points. Nine of the ten eigenvalues lie in $[-75 \;\; -1]$, while the last one is lower than -350. Setting a threshold at $\tau = -90$, it can be deduced that the system has one fast dynamic and nine slow dynamics:

$$x_F(t) = X_{DCO}(t) \tag{49}$$

$$x_S(t) = [\,S_O(t) \;\; S_{NH}(t) \;\; S_{NO}(t) \;\; X_{BH}(t) \;\; X_{BA}(t) \;\; S_I(t) \;\; X_I(t) \;\; S_{ND}(t) \;\; X_{ND}(t)\,]^T \tag{50}$$

4.3 Singular Multi-model Representation for ASM1

The methodology proposed previously, in Sect. 2, is applied here to obtain a multi-model structure for the ASM1 model. Based on the identification and the separation of the fast and slow dynamics, the obtained MM is singular.

Considering the process Eq. (46), it is natural to define the following premise variables since they mainly contribute to the definitions of the nonlinearity of the wastewater system:

$$
\begin{aligned}
z_1(x,u) &= \frac{q_{in}(t)}{V} \\
z_2(x,u) &= \frac{X_{DCO}(t)}{K_{dco}+X_{DCO}(t)}\frac{S_O(t)}{K_{oh}+S_O(t)} \\
z_3(x,u) &= \frac{S_O(t)}{K_{o,a}+S_O(t)}\frac{S_{NH}(t)}{K_{nh,a}+S_{NH}(t)} \\
z_4(x,u) &= S_{ND}(t) \\
z_5(x,u) &= \frac{X_{DCO}(t)}{K_{dco}+X_{DCO}(t)}\frac{S_{NO}(t)}{K_{no}+S_{NO}(t)}\frac{K_{oh}}{K_{oh}+S_O(t)} \\
z_6(x,u) &= \frac{\frac{X_{ND}(t)}{X_{BH}(t)}}{K_{dco}+\frac{X_{DCO}(t)}{X_{BH}(t)}}\left[\frac{S_O(t)}{K_{oh}+S_O(t)}+\frac{\eta_h K_{oh}}{K_{oh}+S_O(t)}\frac{S_{NO}(t)}{K_{no}+S_{NO}(t)}\right]
\end{aligned}
\tag{51}
$$

According to Remark 1, 6 premise variables will result in 64 submodels, which can lead to infeasible LMI condition for the observer design. An alternative is to reduce the number of premise variables by considering some of them as constant terms equal to their mean value in the operating time interval. Figure 3 illustrates the evolution of the premise variables (51). The small variation ranges of the premise variables z_3, z_5 and z_6, compared to the others, encourage to consider their means value (respectively denoted $\widetilde{z_3}$, $\widetilde{z_5}$ and $\widetilde{z_6}$) in the MM construction. Using this approximation, only three premise variables, namely z_1, z_2 and z_4, are considered to design the multi-model, which is thus described by 2^3 submodels.

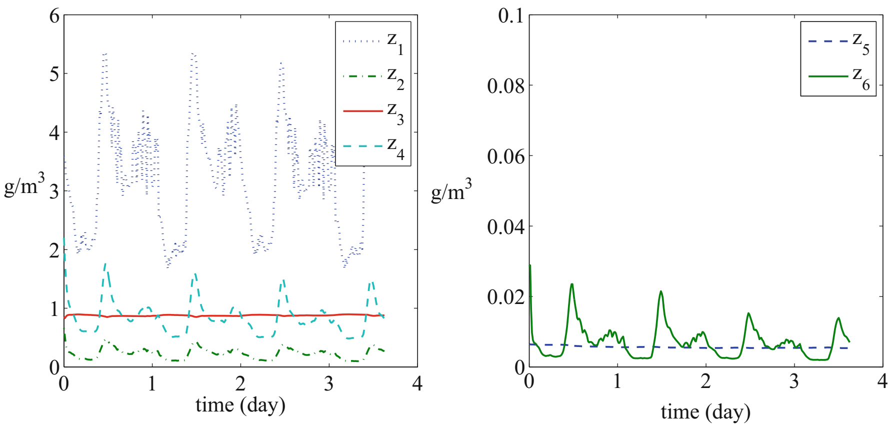

Fig. 3 Evolution of the premise variables $z_1(t), \ldots z_6(t)$

The system (46) can be written in a following Quasi-LPV form with unknown input $\dot{x}(t) = A(x,u)x(t) + B(x,u)u(t) + F(x,u)d(t)$, where the matrices $A(x,u)$, $B(x,u)$ and $F(x,u)$, depending on the premise variables previously defined, are given by:

$$A(x,u) = \begin{bmatrix} a_{1,1} & 0 & 0 & 0 & a_{1,5} & a_{1,6} & 0 & 0 & 0 & 0 \\ 0 & a_{2,2} & 0 & 0 & a_{2,5} & a_{2,6} & 0 & 0 & 0 & 0 \\ 0 & 0 & a_{3,3} & 0 & a_{3,5} & a_{3,6} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{4,4} & a_{4,5} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & a_{5,5} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & a_{6,6} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{7,7} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & a_{8,5} & a_{8,6} & 0 & a_{8,8} & 0 & 0 \\ 0 & 0 & 0 & 0 & a_{9,5} & 0 & 0 & 0 & a_{9,9} & 0 \\ 0 & 0 & 0 & 0 & a_{10,5} & a_{10,6} & 0 & 0 & 0 & a_{10,10} \end{bmatrix}$$

$$B(u) = \begin{bmatrix} z_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & K\,S_{O,sat} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & z_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & z_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & z_1 & 0 \\ 0 & 0 & 0 & 0 & 0 & z_1 \end{bmatrix}, \quad F(u) = \begin{bmatrix} 0 \\ 0 \\ z_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{52}$$

where $z_1 = z_1(u)$, the matrices components $a_{1,1}(x,u) = a_{3,3}(x,u) = a_{4,4}(x,u) = a_{7,7}(x,u) = a_{9,9}(x,u) = -z_1(u)$ and where:

$$\begin{aligned}
a_{1,5}(x,u) &= -\frac{\mu_h}{Y_h} z_2(x,u) + (1-f_p)\,b_h - \frac{\mu_h\,\eta_{NOg}}{Y_h}\widetilde{z_5} \\
a_{1,6}(x,u) &= (1-f_p)\,b_a \\
a_{2,2}(x,u) &= -z_1(u) - K\,q_a \\
a_{2,5}(x,u) &= \frac{(Y_h-1)\mu_h}{Y_h} z_2(x,u) \\
a_{2,6}(x,u) &= -\frac{4.57-Y_a}{Y_a}\mu_a\,\widetilde{z_3} \\
a_{3,5}(x,u) &= (i_{xb}-f_p\,i_{xp})b_h - i_{xb}\,\mu_h\,z_2(x,u) - i_{xb}\,\mu_h\,\eta_{NOg}\,\widetilde{z_5}
\end{aligned}$$

$$
\begin{aligned}
a_{3,6}(x,u) &= (i_{xb} - f_p\, i_{xp})\, b_a - (i_{xb} + \frac{1}{Y_a})\mu_a\, \widetilde{z_3} \\
a_{4,5}(x,u) &= \frac{Y_h - 1}{2.86\, Y_h}\mu_h\, \eta_{NOg}\, \widetilde{z_5} \\
a_{4,6}(x,u) &= \frac{1}{Y_a}\mu_a \widetilde{z_3} \\
a_{5,5}(x,u) &= \mu_h\, z_2(x,u) - b_h + z_1(u)\left[\frac{f_w(1+f_r)}{f_r+f_w} - 1\right] + \mu_h\, \eta_{NOg}\, \widetilde{z_5} \\
a_{6,6}(x,u) &= z_1(u)\left[\frac{f_w(1+f_r)}{f_r+f_w} - 1\right] - b_a \mu_a\, \widetilde{z_3} \\
a_{8,5}(x,u) &= f_p b_h \\
a_{8,6}(x,u) &= f_p b_a \\
a_{8,8}(x,u) &= \left[\frac{f_r(1-f_w)}{f_r+f_w} - 1\right] z_1(u) \\
a_{9,5}(x,u) &= -k_a\, z_4(x,u) + k_h\, \widetilde{z_6} \\
a_{10,5}(x,u) &= (i_{xb} - f_p\, i_{xp}) b_h - k_h\, \widetilde{z_6} \\
a_{10,6}(x,u) &= (i_{xb} - f_p\, i_{xp}) b_a \\
a_{10,10}(x,u) &= \left[\frac{f_r(1-f_w)}{f_r+f_w} - 1\right] z_1(u)
\end{aligned} \tag{53}
$$

The decomposition of the three premise variables—$z_1(u)$, $z_2(x,u)$ and $z_4(x,u)$—from (51) is realized by using the convex polytopic transformation (5). The scalars $z_{j,1}$ and $z_{j,2}$ are defined as in (6a)–(6b) and the functions $F_{j,1}(z_j(x,u))$ and $F_{j,2}(z_j(x,u))$ are given by (7a)–(7b) for $j = 1,2,4$. By multiplying the functions $F_{j,\sigma_i^j}(z_j(x,u))$, the $r = 8$ weighting functions $\mu_i(z(x,u))$ $(i = 1,\cdots,8)$ are obtained and illustrated in Fig. 4:

$$
\mu_i(z(x,u)) = F_{1,\sigma_i^1}(z_1(u)) F_{2,\sigma_i^2}(z_2(x,u)) F_{4,\sigma_i^4}(z_4(x,u)) \tag{54}
$$

The constant matrices A_i, B_i and F_i defining the eight submodels, are determined by using the matrices $A(x,u)$, $B(u)$, $F(u)$ and the scalars z_{j,σ_i^j}:

$$
A_i = A(z_{1,\sigma_i^1}, z_{2,\sigma_i^2}, z_{4,\sigma_i^4}) \tag{55a}
$$

$$
B_i = B(z_{1,\sigma_i^1}) \tag{55b}
$$

$$
F_i = F(z_{1,\sigma_i^1}) \qquad i = 1,\ldots,8,\ j = 1,2,4 \tag{55c}
$$

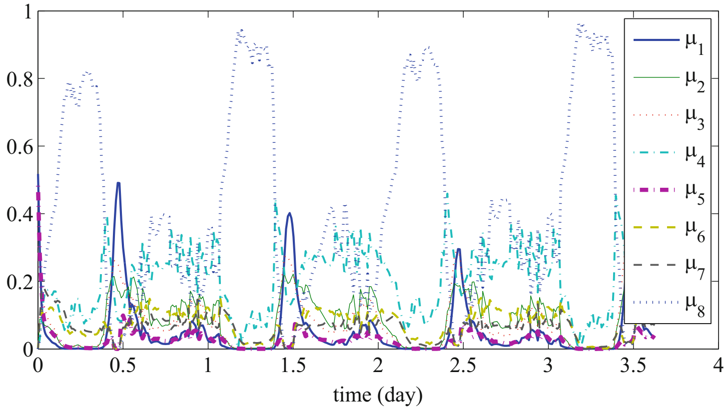

Fig. 4 Weighting functions $\mu_i(z(x,u))$

According to the fast and slow variable separation (49), performed in Sect. 4.2, the matrix $\bar{E}$ of the singular multi-model formulation (23) is defined by:

$$\bar{E} = \mathbf{diag}\begin{bmatrix}0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1\end{bmatrix} \tag{56}$$

Thus, the nonlinear model (43)–(46) can be written as the following singular MM:

$$\bar{E}\dot{x}(t) = \sum_{i=1}^{r} \mu_i(x,u)[A_i x(t) + B_i u(t) + F_i d(t)] \tag{57a}$$

$$y(t) = Cx(t) + Du(t) + Gd(t) + \delta(t) \tag{57b}$$

where D and G are null matrices of appropriate dimensions, C is defined by

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{58}$$

and where $\delta(t)$ is a measurement noise modeled by a zero mean random signal.

In order to highlight and quantify the accuracy of the approximation of the ASM1 (46), provided by the singular MM (57), the average relative deviation (ARD) is computed for each state variable by:

$$ARD_j = \frac{1}{n_t} \sum_{i=1}^{n_t} \left(\frac{\left| x^j_{MM}(i) - x^j_{ASM1}(i) \right|}{x^j_{MM}(i)} \right) \times 100\,\%, \quad \text{for } j = 1, \ldots, n_x \tag{59}$$

where n_t is the number of data points. The following obtained values of the ARD:

$$ARD = [1.85 \quad 0.71 \quad 0.28 \quad 5.60 \quad 1.37 \quad 0.25 \quad 0.05 \quad 0.07 \quad 2.31 \quad 0.45]\ \%$$

confirm that the state trajectories of the original system (46) and of the approximated one (57) are close. In conclusion, the ASM1 model (46) can be rewritten under the singularly MM with unmeasurable premises, as described in (26) and the state estimation, proposed in Sect. 3, can be applied.

4.4 Unknown Input Observer Design

As seen is Sect. 3, a nonsingular multi-observer (32) can be designed based on the singularly perturbed multiple model (26) or (29). The matrices $\bar{E}$, A_i, B_i, $\bar{F}_i$, C and $\bar{G}$ of (29) are defined by (55)–(58) and the weighting functions are defined in (54).

Let us consider the model uncertainties $\theta_1^A(t) = \theta_1(t)$, $\theta_2^A(t) = \theta_2(t)$ and $\theta_3^A = \theta_3(t)$ caused by the deviation of three model parameters from their following nominal values: $f_{ss} = 0.79$, $\eta_{NOg} = 0.8$ and $K_{no} = 0.5$ involved in the ASM1 model (46) (see Fig. 5). The uncertain parameter f_{ss} influences the dynamic of the states X_{DCO}, S_O, S_{NH}, X_{BH}, S_{ND} and X_{ND}. The parameter η_{NOg} interferes with the dynamic of the states X_{DCO}, S_{NH}, S_{NO}, X_{BH}. The uncertain parameter K_{no} affects the dynamics of X_{DCO}, S_{NH}, S_{NO}, S_{ND} and X_{ND}. Applying Theorem 1, the observer matrices N_i, G_i, L_i and T_2 are deduced, by using the specific solver Yalmip for convex optimization problems (Löfberg 2004, 2012).

In Fig. 6 the state variables and their estimates are presented. Figures 7 and 8 represent the unknown input $d(t)$ and the known input $u(t)$, respectively. The $\mathcal{L}_2$ gain of the transfer from $\omega(t)$ to $e(t)$ is bounded by $\gamma = 4.5$. The reconstructed output $\hat{y}(t) = C\hat{x}(t)$ of the system is presented in Fig. 9. One can see that although a noise is added on the output measurements, output and state estimation are

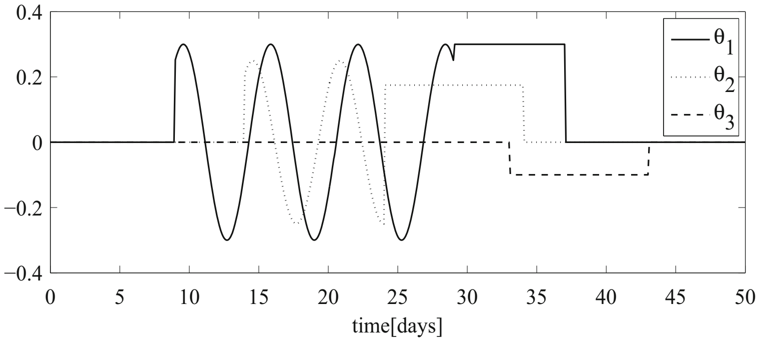

Fig. 5 Time varying model uncertainties

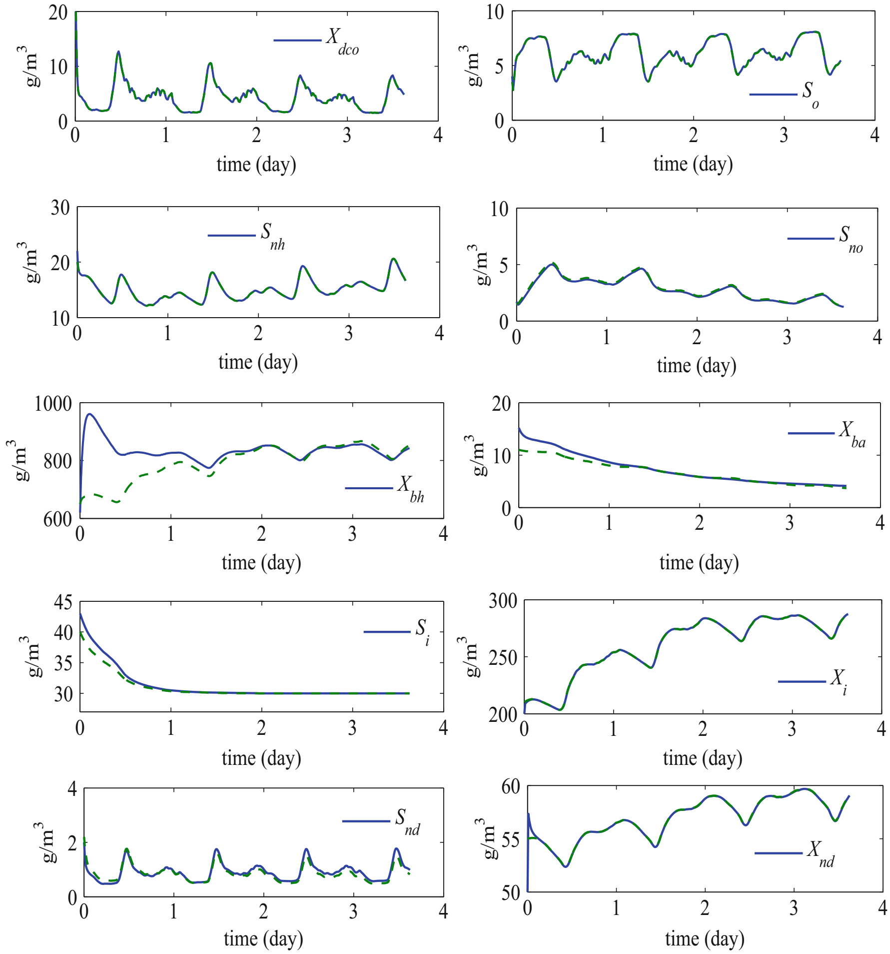

Fig. 6 Original and estimated state variables of the ASM1 model

of good quality. One can see that the state and output estimation are of good quality, even if the observer design is based on a reduced system with some simplifying assumptions (fast dynamic considered as algebraic relation, constant premise variables) and even if a measurement noise is added on the system outputs. The VAF (Variance Accounted For) coefficient between two signals is chosen to asses the state estimation quality. The VAF between the ith component of x and $\hat{x}$ is defined by: $VAF_{x_i} = \left[1 - \frac{var(x_i - \hat{x}_i)}{var(x_i)}\right] 100\,\%$ (a VAF of $100\,\%$ corresponds to identical signals). The VAF coefficients computed for the original and estimated the state variables are:

$$VAF_x = [92.71;\ 96.45;\ 95.35;\ 95.53;\ 70.25;\ 86.75;\ 99.13;\ 98.73;\ 82.91;\ 96.02]$$

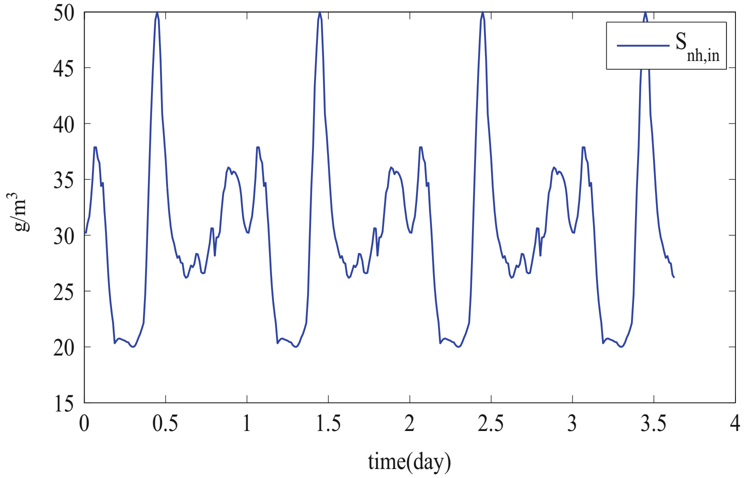

Fig. 7 Unknown input of the ASM1 model

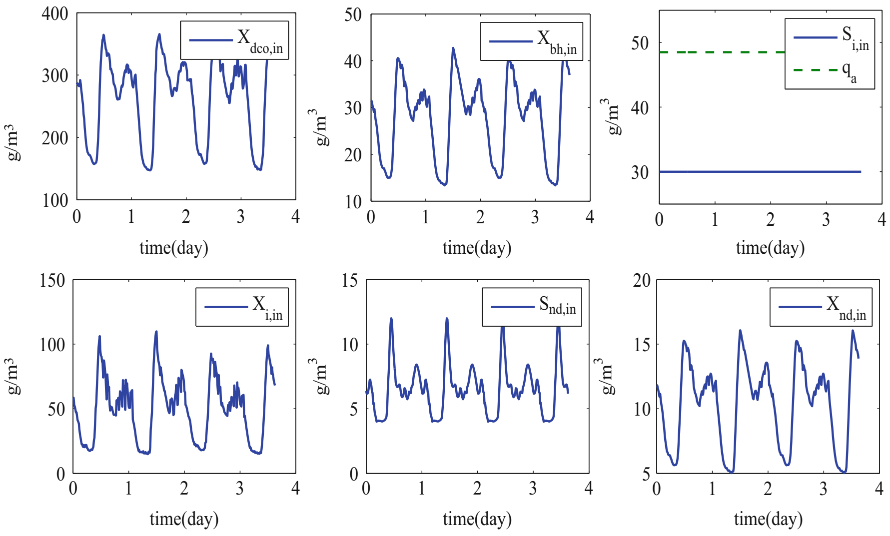

Fig. 8 Inputs of the ASM1 model

5 Conclusion

In this chapter, some tools for model complexity reduction and their application for observer design were exposed and illustrated on an environmental process. Firstly, a method to rewrite, with no information loss, a generic nonlinear dynamic model as a multi-model with linear submodels and state dependent premise

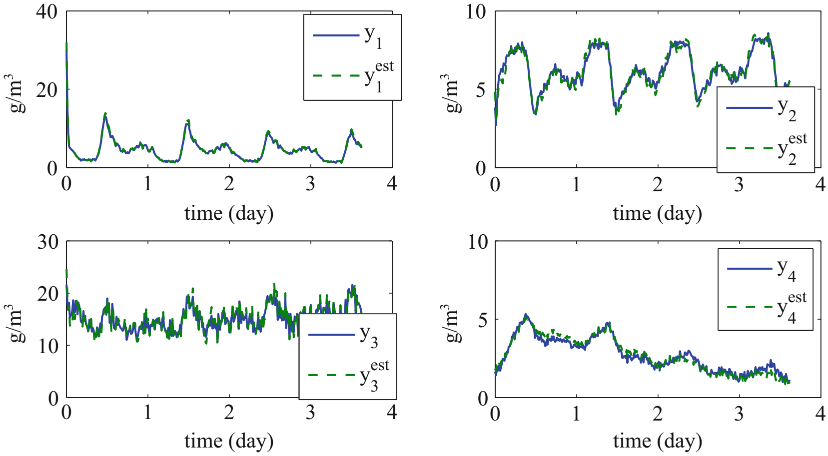

Fig. 9 Estimated outputs for the ASM1 model

variables was proposed. Since several multi-model forms can be obtained from the original nonlinear model, some choice criteria were recalled in order to select the most suitable form, according to its use (performance analysis, observer/controller design, fault diagnosis etc.). Secondly, slow and fast dynamics of the model are identified and separated and the MM is modified according to this separation. The fast dynamics being taken into account as algebraic relations, then a singular multi-model is obtained. In order to estimate the state of such systems, even when all the inputs are not known (unknown input allow to model not only external disturbances or unmeasured system inputs, but also modeling errors), an observer for singular multi-model with unmeasurable premise variables and affected by unknown inputs is proposed. The observer design, aiming at minimizing the influence of the unknown inputs, noise measurements and modeling uncertainties on the estimation, is formulated as an LMI optimization problem. The observer provides the estimation of the slow and fast state variables. Finally, an application to a realistic model of a wastewater treatment plant has been exposed and gives good results using the complete ASM1 model.

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A Few Reflections on the Quality of Emergence in Complex Collective Systems

Vincenzo De Florio

Abstract A number of elements towards a classification of the quality of emergence in emergent collective systems are provided. By using those elements, several classes of emergent systems are exemplified, ranging from simple aggregations of simple parts up to complex organizations of complex collective systems. In so doing, the factors likely to play a significant role in the persistence of emergence and its opposite are highlighted. From this, new elements for discussion are identified also considering elements from the philosophy of Leibniz.

1 Introduction

Emergence: that "magic" that produces something new and more from the interactions of a set of parts—sometimes something totally unexpected and even bewildering. Something that manifests itself with a "strength", or an energy, or a *meaning*, that is way greater than the one exhibited by the individual parts that make the whole up.

Emergence as well as the factors responsible for its manifestation are the main characters in this work. My focus shall be quite general and will try to characterize the emergence that manifests itself from collections of simple objects up to complex organizations of complex systems. Examples shall be considered among artificial, natural, and social systems. Far from an exhaustive treatise, this may be considered as a first step towards a characterization of those factors that sustain the manifestation of emergence in complex collective systems when subjected to change. The word "change" shall assume meanings that are specific of the considered level, or "scale," of the system at hand:

V. De Florio (✉)
Vlaamse Instelling voor Technologisch Onderzoek, Remote Sensing Department, Boeretang 282, 2400 Mol, Belgium

Vrije Universiteit Brussel, Global Brain Institute & Evolution, Complexity and COgnition group, Pleinlaan 2, 1050 Brussels, Belgium
e-mail: vincenzo.deorio@vito.be

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- In the case of simple objects and systems, change shall refer to, e.g., the consequences of wear-out, defects, physical failures, or operational conditions beyond those expected or foreseen is some specification document.
- In the case of more complex collective systems, change shall include the effect of forces that disrupt or strengthen the cohesion of the social system.

I will use the term "*quality of emergence*" (QoE) to refer to the cumulative effect of the above factors and changes.

In what follows I first present, in Sect. 2, three elements useful for the characterization of the QoE in complex collective systems. Those elements are then used in Sect. 3 to define several classes of emergent systems. Some remarks on related concepts—resilience and failure semantics—are then given in Sect. 4. Preliminary lessons learned are finally summarized in Sect. 5.

2 Preliminaries

It is already emergence something that appears to "spring" from the simple interactions of simple interconnected objects. Let us make use of an example. If you consider a car and its parts, we see that among all of the possible combinations of the latter there are some that allow the union of the parts to become something else, something *greater*; something that makes the new element respond to a new and specific definition: in this case, the definition of car.

Here is a first, simple example of emergence: a tool that is produced by the combination of a set of components. We observe how in this case, from a systemic point of view, the compound differs only slightly from the components. Both components and compound are "simple" systems. Cogs made of cogs. Furthermore we observe how even the "glue" that holds together the components and, in fact, *realizes* the tool, is in this case very much simple: it is made of physical connections based on the material properties of the components; on their shapes; and on auxiliary components the purpose of which is to ensure the persistence of the identity of the compound; to "keep it together", at least for a certain period of time and under certain operating conditions.

The name of this "glue" is **organization**. Emergency is therefore a property of a compound formed from components organized into a *whole*. Organization is what holds together and puts in relation the components with one another. My stance here is that these three aspects—the systemic characteristics of components, of the compound, and of the "glue"—constitute three of the key elements to characterize an emerging system and its quality.

A first aim of this paper is to lay the foundation to a future classification of "emergent systems" based on the just mentioned triplet.

Two methodological assumptions are introduced in the rest of this section.

2.1 Methodological Assumptions and Preliminary Steps

Components, compound, and organization are three elements that I selected to operate a classification of emergent systems. In order to distinguish among compound and component systems, in what follows I propose to use a general systems classification such as the one introduced in Rosenblueth et al. (1943) or Boulding (1956), or their augmentations (De Florio 2015b). By means of one such set of classes it is possible to introduce the following definitions.

Definition 1 (Systemic Quality). In what follows I shall refer to the systemic quality of a component or a compound as to one of the following classes:

P: systems only capable of passive behavior; in other words, objects.
$\neg$T: systems capable of purposeful, non-teleological behavior—so-called servo-mechanisms.
T: teleological (that is, reactive) systems. These are systems that embed a feedback loop.
T^+: more-than-teleological systems. This class includes, among others, extrapolative, learning, autonomic, adaptive, and antifragile systems (De Florio 2014a; Jones 2014; Taleb 2012).

Definition 2 (Total Order on the Set of Systemic Qualities). A total order on the set of systemic classes mentioned in Definition 2.1 is introduced as follows:

$$\mathrm{P} \prec_\sigma \neg\mathrm{T} \prec_\sigma \mathrm{T} \prec_\sigma \mathrm{T}^+.$$

For any two systems a and b, if $a \prec_\sigma b$ we shall say that a is *less evolved* than b. To refer to the systemic quality of any system a we shall use notation $\sigma(a)$.

What just done for systems is now done for organizations.

Definition 3 (Organizational Quality). I shall refer to the organizational quality of a set of components realizing a compound as to one of the following classes:

$+$ Juxtaposition. This is not an organization *sensu proprio*; rather, it is a simple grouping of elements. Emergence is in this case a consequence of the additive property of a physical quantity.

Ξ Strictly hierarchical organizations, characterized by top-down flow of control and bottom-up flow of feedbacks (autocracy). Several traditional human-based organizations are based on this class.

Ξ^+ Nested compositional hierarchies. This type of organization is based on so-called "principle of increasing inclusiveness", in which "entities at one level are composed of parts at lower levels and are themselves nested within more extensive entities" (Tëmkin and Eldredge 2015). Widely adopted in nature, class Ξ^+ makes a systematic use of modularity, one of the key factors leading to the emergence of complexity—what is defined in Wagner and Altenberg (1996) as "the evolution of evolvability."

$\Xi^\times$ This is the class of what I call "metarchies": more-than-hierarchical organizations. This includes, among others, heterarchies (Stark 1999) and exception-based hierarchies (De Florio 2015c), such as sociocracy (Buck and Endenburg 2012) and socio-fractal organizations (De Florio 2013; De Florio and Pajaziti 2015a; De Florio and Pajaziti 2015b; De Florio et al. 2013).

As it has been done for the systemic quality, it is now possible to introduce a total order for organizations.

Definition 4 (Total Order on the Set of Organizational Qualities). I define a total order between the classes introduced in Definition 2.1 as follows:

$$+ \prec_o \Xi \prec_o \Xi^+ \prec_o \Xi^\times.$$

If $a \prec_o b$ I shall say that a is less evolved than b. In what follows I shall use symbol $o(a)$ to refer to the organizational quality of any organization a.

To simplify the notation, when this can be done without introducing ambiguity, I will make use of symbol "$\prec$" to refer to either of $\prec_\sigma$ and $\prec_o$.

In what follows, I shall refer to the emergent systems as either Whole or Compound and to its elements as either Parts or Components.

3 Elements of a Classification of Emergent Systems

Here I provide some elements of a classification of emergent systems.

One of the lower levels, if not the lowest, is the one of systems operating as LED lamps. Those are systems in which

- *simple components* (more precisely, systems whose behavioral class is at most $\neg$T)...
- ...*implement a system as simple as their components* (again, at most $\neg$T, although characterized by non-trivial emergent properties)...
- ...*by means of a simple organization* ("simple" meaning here "at most of class Ξ").

A LED lamp is in fact composed from simple...LED's, which, however, constitute a more powerful light source. Interestingly enough, such light source is characterized by *additional* properties—properties that are not present in the constituent elements. For instance, a LED lamp is characterized by low power consumption.

But there also more "subtle" and I would say more intriguing properties that in this case characterize and *distinguish* the compound from the components—the Whole from its Parts. One such property is *graceful degradation*. While an ordinary lamp has a "binary" failure semantics (it is either "working" or not at all), a LED lamp has what I would refer to as a *fuzzy* failure semantics. In fact, there is an ample spectrum of transition states in between "working" and "not working"! I believe it is interesting to highlight that in this case the "glue", namely the organization of the LEDs in an LED lamp, is perhaps the simplest possible. The "cohesion" that allows the Whole to emerge from its Parts is in fact based on simple physical laws. The light expressed by the Whole is produced through additive synthesis of the lights emitted by the Parts—which, among other things, makes it possible to easily vary the emerging color of the lamp (Schubert 2006). By referring to the metric proposed in Sect. 1, organization is in this case of class "+".

We can conclude that a LED lamp provides us with a first "class" of emergent systems:

$$(\neg\mathrm{T}, \neg\mathrm{T}, +). \tag{1}$$

Triplet (1) is representative of systems in which both compound and components are characterized by at most purposeful, non-teleological behaviors (Rosenblueth et al. 1943) and the organization is of the additive class $+$. As already pointed out, more than of an organization it may make more sense in this case to talk of a "grouping"—a combination of the Parts. It is worth remarking that the emergent properties gradually appear with the juxtaposition of the components, and gradually disappear with their removal or their disintegration.

Definition 5. Emergent systems characterized by the triplet (1) will be called in the following LED systems.

In what follows I shall not engage in a comprehensive classification, whose attempt I aim to address in subsequent works. Aim of this paper is to pave the way for such an endeavour by defining some classes of emergent systems of particular interest—as well as to reflect about possible relationships between those classes and emergence "meta-properties" (namely, properties related to the property of emergence.)

3.1 Hierarchies with Components Less Advanced than the Compound

Here I will discuss the family of emergent systems that are characterized by the adoption of a hierarchy (thus an organization of either Ξ or Ξ^+ class) and with $o(\text{Parts}) \prec o(\text{Whole})$. Again, this is not meant as an exhaustive treatise—rather, it is an exemplification of several of the members of a family of emergent systems.

3.1.1 Organs

I shall call "organs" those emergent systems that are made of passive-behaviored components ("objects", or "cogs") that are assembled into a purposeful, non-teleological behaviored Whole—for example, a servomechanism. I shall use the following notation:

$$(\mathrm{P}, \neg\mathrm{T}, \Xi), \tag{2}$$

"Assembled" here stands for a rigid and immutable hierarchy (namely, class Ξ).

Definition 6. Emergent systems characterized by the (2) triplet will be called in the following as **organs**.

In the case of organs, the identity of the system (and thus the persistence of its "quality") is purely related to the mechanical cohesion of the parts within the whole. In other words, there are no "centrifugal" forces (Dominici 2011, 2013, 2014) leading the individual Parts to disrupt cohesion, because the parties are mere objects. Persistence of identity and emergence is affected by wear-out, defective parts, defective assemblage, etc.

3.1.2 Systems of Organs

In this class of emergent systems, organs are assembled to compose an autonomous system capable of teleological/reactive behaviors (Rosenblueth et al. 1943). In this case I shall use notation

$$(\neg \mathrm{T}, \mathrm{T}, \Xi). \tag{3}$$

Definition 7. Non-teleological Parts hierarchically united to form a teleological system, as expressed by the (3) triplet, shall be called in what follows a **system of organs**.

The autonomic nervous system of animals is an example of a system of organs. Persistence of resilience is usually a result of wear-out, malfunctioning, defective organs, or external conditions.

3.1.3 Organisms

Systems of organs, organized into autonomous systems characterized by autonomicity, proactivity, and other advanced capabilities [in some cases sentience, self-awareness, and antifragility (De Florio 2015b; Jones 2014)], are called in what follows **organisms**. More formally, an organism is characterized by the following triplet:

$$(\mathrm{T}, \mathrm{T}^{+}, \Xi^{+}) \tag{4}$$

and is defined as follows:

Definition 8. Teleologically behaviored Parts producing a more-than-teleologic Whole and organized as nested compositional hierarchies as expressed by the triplet (3.1.3) shall be called in what follows **organisms**.

A fractal organization of systems of organs, as exemplified by the human body, *realizes* an organism.

Organisms may be characterized by a “body”—for instance, a physical, a legal, or a social “body”. Depending on the nature of its body, an organism may be more or less sensitive to disruptive forces such as wear-out, aging, external threats, parasitism, and extreme “individualism.”

3.1.4 Societies

In what follows, an organization of organisms shall be called a society. More formally:

Definition 9. A society is an emergent system characterized by the following triplet:

$$(T^{+}, T, \ \xi), \tag{5}$$

ξ being *any type* of organization.

As apparent from Definition 3.1.4, societies are a peculiar case of emergent systems, in that they are an organization of highly evolved Parts that produce a Whole that is less evolved than its Parts. What is also remarkable is that said organization may vary across the whole range of organizational classes.

I shall now focus my attention on four sub-classes of societies, defined as follows.

Definition 10 (Parasitic Society). An organization of organisms (i.e., a society) that provides returns that are beneficial to only some of the involved organisms shall be called a **parasitic society**.

Sentinel species (van der et al. 1999) are an example of organisms *employed* for a purpose defined by other organisms. Canaries for instances have been used for a long time to alert miners of the presence of of dangerous concentrations of toxic substances—e.g., carbon monoxide and dioxide, or methane (De Florio 2015b). In parasitic societies, persistence of emergence is guaranteed by the impossibility for the Parts to leave the Whole. Other examples that come to mind are that of social systems including so-called slaves, as it was the case, e.g., in ancient Egypt, or social systems including a class deprived of most of the civil rights, as it was for instance for the *Tiers État*, the weakest of the estates in the organization of the French state before the Revolution.

Definition 11 (Ecosystem). A society that sustains returns that are mutually satisfactory for the Parts and the Whole, and that is beneficial to all parties involved—without explicitly privileging some of the parties involved—shall be called in the following an **ecosystem**.

An exemplary ecosystem is a beehive (Maeterlinck 1910). In this case *a mutualistic relationship exists between Parts and Whole*. This is similar to what happens in nature across the scales of natural systems. In fact this phenomenon takes place even between societies—the natural kingdom of animalia and that of plantae being a well-known example.

The organisms of an ecosystem are able to establish a *harmony* of sorts, recognizing the role that the Whole plays for the Parts and vice-versa. Persistence of emergence "emerges naturally" because of said sustained harmony.

An interesting paradox is that said harmony is stronger when the organisms that constitute the society have not developed a strong sense of individuality—thus their persona can more easily blend with the persona of the Whole (De Florio 2014c). Human societies are a classic case in which disharmony between Parts and Wholes may manifest itself. The resulting "tragedies of the common" (Hardin 1968) have been impacting severely on the sustainability of our species.

Definition 12 (Factory System). A third sub-class of societies is a **factory system**, namely one that provides unbalanced returns that, although being mutually beneficial, are biased towards a subset of the Parts.

The Industrial Revolution and subsequent times produced many extreme cases of factory systems—ironically rendered by Charles Chaplin in his renowned "Modern Times" as a human organism caged into a production mechanism.

Remarkable traits of a factory system are the minimal or absent identification of the components with the compound. The Parts typically do not blend into the Whole while the Whole often does not recognize or value the individuality of the Parts, which are regarded in the same way as interchangeable parts in a manufacturing system. Cohesion and persistence of emergence are a consequence of environmental conditions that motivate the parts to accept their role of components despite the unbalanced returns.

Definition 13 (Defense System). A fourth sub-class of societies is a **defense system**, namely a society of organisms whose major sought after return is survivability of the Whole and the Parts in the face of an external threat.

The external threat (the "foe") personifies the reason for cohesion and reduces centrifugal forces despite the adoption of rigid forms of hierarchy (typically, Ξ). Persistence of emergence is also strengthened by specific internal regulation (in the case of armed forces, this is called "military justice").

4 Resilience and Failure Semantics

4.1 Resilience as a Dynamic Property

In Sect. 2 I briefly hinted at a crucial aspect that has not been further developed in the present article. I refer to resilience, namely a compound's persistence of identity (De Florio 2015a; De Florio 2015b). There is clearly a strong link between QoE and resilience, as a system's identity prescribes and details the emergence of a number of expected properties, traits, or characteristics.

It is important to realize that, as QoE, also resilience is a *dynamic* property: a compound retains its characteristics "for a certain period of time and under certain operating conditions". Resilience is thus a trait that may appear, be sustained for a while, and then disappear. As a consequence, rather than considering QoE as an absolute property, we should consider a reference QoE and match it continuously with an actual, observed, QoE. The already mentioned example of a car applies here too: the concept of car entails a number of reference properties—for instance, the car should move as we expect it to do; should be controllable by means of an agreed upon, standard interface; and so on. When the observed properties of a car drift away from those reference properties, the car looses its identity. In other words, in order to be a car, a system should "behave" like a car. When the observed behaviors do not match anymore the expected ones, the car is no more resilient. The approach I followed in De Florio (2014a) and De Florio and Primiero (2015) is to measure resilience by considering a drift from the reference quality—in fact, a distance. Such drift, or distance, is also a dynamic system—thus a property that varies in time. In the cited papers I highlighted how different resilience classes may be associated to different ways for the drift to vary in time. A more fine-grained classification of QoE should also consider the resilience class exhibit by the system under consideration.

4.2 Resilience as a Compound's Property

A way to model a compound's resilience is possibly given by considering the *energy* that binds together the components into the compound and allows them to fulfill the roles prescribed by the organization. Said energy is finite. When it goes below a given threshold, a component and possibly its compound lose their identity. In order to prolong the life of the compound, certain components may be replaced—as an old tire is replaced with a new one, for instance. When such process can be done autonomously, then the system is said to self-repair.

In some cases this replacement is difficult or impossible to achieve. We can replace a "heart" though we can not replace a "brain". In such a case, the system disintegrates—it "dies". A compound characterized by a certain aggregation quality breaks down into its components, thereby loosing the identity-of-the-compound. Like a castle of cards that fall down, the compound that once stood and now stands no more becomes again "simply a pack of cards". The ancient ones reflected on this very phenomenon and associated it with *sadness*. Asclepius's Lament in the Corpus Hermeticum (Mead 1906) stands for the sorrow associated with this loss of emergence[1]—especially when induced by external forces; with "divinity" leaving the living statues of Horus and "returning from Earth to Heaven" (Coppens 2016). Said "divinity", which Giordano Bruno calls "profound magic", is indeed the miracle of the persistence of identity (Bruno Nolano 2000).

4.3 A Note on Failure Semantics

In Sect. 3 we briefly mentioned the role of failure semantics—the way a system loses its resilience and stops manifesting its emerging properties. As we exemplified already, systems with the same purpose may fail very differently. This change of failure semantics is what we observe when moving for instance from the traditional concept of car to that of drive-by-wire car: as already mentioned, although in both cases the purpose is the same, not so are the organizations of the parts across the scales of those systems. The fact that the purpose is the same should not trick us into believing that both systems shall fail the same way. A mechanical car often exhibits graceful degradation. Moreover, if an electronic car bumps lightly into a wall, the identity of that car may have suffered in a more subtle, less evident way than the identity of a traditional car. In other words, electronic cars are inherently more "fragile" than traditional ones.

5 Conclusions

In this paper I provided a number of elements towards a classification of the quality of emergence in emergent collective systems. A number of classes of emergent systems has been exemplified, ranging from simple aggregations of simple parts up to complex organizations of complex collective systems. In each class I highlighted those factors that appear to play a significant role in the persistence of emergence or its opposite. A lesson learned while collecting the above results is that apart from classic causes—such as deterioration or wear-out; design faults; defective or non-optimal components, etc.—a significant role in the sustaining of emergence is *harmony* between the Parts and the Whole. Lack of said harmony translates in fact into disruptive forces that minimize identification of the Parts with

[1] "This All, which is a good thing, the best that can be seen in the past, the present and the future, will be in danger of perishing; men will esteem it a burden; and then they will despise and no longer cherish *this whole of the universe*, incomparable work of God, glorious construction, good creation made up of an infinite diversity of forms, instrument of the will of God who, without envy, pours forth his favour on all his work, in which is assembled in one whole, in a harmonious diversity, all that can be seen that is worthy of reverence, praise and love." (Coppens 2016).

the Whole and therefore tend to repel the former from the latter. My conjecture here is that indicators of disharmony may be defined by considering possible mismatches between σ(Components) and σ(Compound), as well as mismatches between σ(Components) and o(Organization).

From the above reasoning, a new element to the present discussion naturally *emerges*: a fourth element to the triplet (compound, components, organization) may be *sustainability*, which I interpret here as a collective system's propensity towards the realization of mutualistic relationships, strengthening identification, and other "centripetal" forces.

A final remark brings me back to my first example, when I considered a car and its parts and I mentioned that among all of the possible combinations of the parts there are some that allow the compound to become something "else". I think it is important to remark here how emergence indicates the birth of a new concept, of a new and unique "substance" responding to a new *definition*—in Aristotelian and Leibnitian terms (Burek 2004; De Florio 2014b,d). Moreover, "substance" is the materialization/implementation/*real*ization of an abstract concept—what Leibniz calls a *monad*; thus, it is a "physical" rendition of a purely conceptual idea. It is again Leibniz that suggests that QoE may be better assessed by considering an intrinsic, an extrinsic, and a "social" element:

Intrinsic element: The "design choices" of which elements to combine and how. This, in a sense, is the "abstract code" of the system being considered.

Extrinsic element: The "implementation choices" of which "physical" parts; organs; organisms; and societies to employ in order to produce a material instance of the abstract code.

Social element: The "compossibility" (compatibility) of the material instance when integrated in a society of other substances (Leibniz and Strickland 2006); a concept that anticipates Darwinian fitness and evolution.

A preliminary discussion of the above elements is available in the draft paper (De Florio 2016) and shall be further elaborated in future contributions.

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Link Structure Analysis of Urban Street Networks for Delineating Traffic Impact Areas

Tzai-Hung Wen, Wei-Chien-Benny Chin, and Pei-Chun Lai

Abstract With the growing number of developing large-scale cities, *traffic congestion* has becomes a global issue. Traffic congestion could be attributed to *topological structure* of street network and *traffic flow concentration*. It is necessary to investigate these two factors simultaneously to solve traffic congestion. Therefore, this study proposed an innovative analytical procedure of ranking algorithm, the *Flow-based PageRank (FBPR)*, for investigating the traffic flow concentration, complexity of street network structure and traffic impact areas. By overlapping these factors, street segments prone to traffic congestion are identified. A network modularity algorithm is used for delineating the traffic impact areas that will be affected by traffic congestion. Our results indicate that only relying on the topological structure of the street network, this framework could identify the Central Business Districts (CBD), and the areas proximate to the stations of the combination of MRT and train railway systems are prone to traffic congestion. Meanwhile, the delineation of traffic impact areas could be spatially targeted at priorities of traffic improvement for city planners.

1 Introduction

With a growing number of developing cities, traffic congestion has become a global issue. In developing countries, the capacity of streets cannot meet the demands of drivers, causing congestion. Some cities in developed countries have special street network structures that also cause traffic congestion. Many cities suffer from congestion, and some cities stipulate congestion pricing to reduce traffic by requiring drivers to pay a surcharge. Congestion can be grouped into different types; slight congestion such as single interactions only makes the velocity of individual vehicles slower, whereas severe congestion such as network and control congestion

T.-H. Wen (✉) • W.-C.-B. Chin • P.-C. Lai
Department of Geography, National Taiwan University, 10617 Taipei City, Taiwan
e-mail: wenthung@ntu.edu.tw; d03228002@ntu.edu.tw; r01228013@ntu.edu.tw

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(Vickrey 1969) slows the velocity of the whole network and requires additional traffic control. Congestion increases commuting times and fuel usage and causes environmental deterioration.

Traffic congestion is a spatio-temporal process (Kerner 1999). When the traffic volume increases on a street, the flow rate will decrease but the flow rates upstream remain the same, resulting in congestion (Kerner 1999). Apart from being triggered by recurring factors such as inadequate capacity or recurrent weather (Kwon et al. 2006), congestion is often triggered by unexpected factors such as accidents, lane closures, and special events (Kwon et al. 2006). Therefore, to measure and detect unexpected congestions have become an important issue for resolving traffic jams. Physical traffic congestion can be measured by using a fundamental diagram (FMD) which illustrates the absolute congestion state under a certain volume, speed, and density. However, the feeling of psychological congestion is relative. Some people are accepting of slight congestion, whereas others are not; thus, fuzzy logic has been discussed for the evaluation of congestion (Lu and Cao 2003; Pongpaibool et al. 2007). Some studies focus on developing methods to detect congestion, whether it is psychological or physical congestion. In early studies of congestion, point-based or short-section (for examining volume over a unit distance) detectors were used (Coifman 2003; Gall and Hall 1989). In recent studies, development of vehicle-to-vehicle systems has risen (Bauza and Gozálvez 2013; Lakas and Shaqfa 2011; Yang et al. 2004). A vehicle-to-vehicle system is a dynamic, non-location-based set of detectors. A vehicle-to-vehicle system utilizes nodes on the street-sides and the vehicle and uses short-range communication equipment to inform closed nodes of the current state of movement. The vehicle as a node is moving and the street side nodes are fixed and connect to a management center. By analyzing the dynamic characteristics of traffic movement, unexpected congestion can be detected, and the management center can make better decisions for traffic control.

From the view of transportation infrastructure, traffic congestion is related to the topological complexity of the streets network, in terms of turning probability. If the street structure is designed to be more complex, the moving vehicles might be easily turning from one street to another, hence, the moving speed would be slower; if the structure is relatively simple, most of the vehicles might be choosing to the same direction, and the moving speed would be faster. In other words, the spatial design of the infrastructure of streets, namely the topological complexity of streets network, would influence the turning probabilities between streets, which would then affect the moving speed along the streets. The streets with higher moving speed could have higher traffic flow rate (number of vehicles passing by per hour) compare with the street segments with lower moving speed. Therefore, if lots of vehicles are moving between street segments with low moving speed, the street would get into a congested situation.

From the view of traveling demand along the streets, the occurrence of traffic congestion is related to the functionalities of destinations, and the connectivities of the street network. The functionality of a destination includes the types of buildings, facilities, or land use at a specific location. In a city, the commercial districts and the area where most office buildings concentrated are where most of the people work.

Therefore, high commuting needs are expected in those areas and the nearby areas. For example, the transportation system near to central business districts (CBD), science and industrial parks, and financial districts would be busier than a residential area. On the other hand, the connectivity of a street represents the degree of the street connected with each other and facilitating people to their destination. As people tend to choose the shortest or fastest ways of moving towards their destination, the selection of the route of each moving person could be dependent on the connectivity of the street system. For example, a street with a higher connectivity to the city center means that it is easier for getting to the city center through the street. Therefore, the high connectivity of the street network could reflect high traffic flow concentration. And it could have high potential to cause traffic congestion.

In sum, traffic congestion could be attributed to topological structure of street network and traffic flow concentration. To solve traffic congestion, it is necessary to investigate these two factors simultaneously. Therefore, the objective of this study is to propose an innovative analytical procedure for investigating the traffic flow concentration, complexity of street network structure, and the traffic impact areas. By calibrating the probability of turning between street segments with the actual traffic volume data, the complexity of the streets topological structure could be measured. The geographical extent of traffic impact areas can be delineated by illustrating geographic regions with high turning probability between street segments. Profiling the characteristics of traffic congestion would provide more comprehensive insights for the city planners, and would also be useful for further understanding of the congestion spreading.

2 Study Framework

The study framework is proposed in Fig. 1. We analyzed the real volumes of vehicle movements along street networks and the proposed flow-based ranking algorithm (Flow-based PageRank, FBPR) to determine the traffic flow concentration (travel

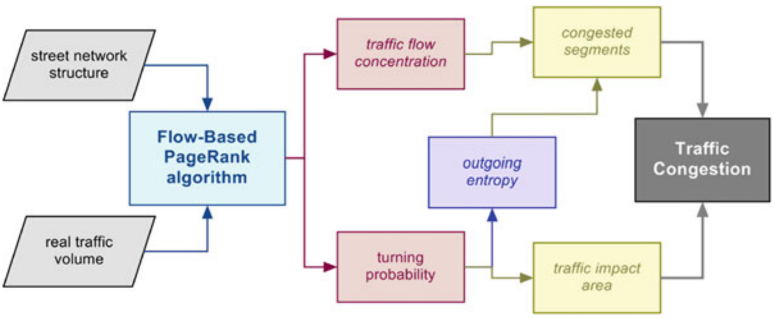


Fig. 1 The conceptual framework

demand), the turning probability (link relationships) and outgoing entropy (topological complexity). Congested segments are defined as the street segments that are prone to traffic congestion. By overlapping these factors, congested segments can be identified. Then, this study used the maximum modularity, a network partition method, to identify the community structure of the traffic flow, which represents the geographic extent of congestion, namely traffic impact area. Through integrating FBPR scores (traffic flow concentration), outgoing entropy, and the traffic impact area, the proposed framework could understand the urban traffic congestion in further. Taipei City, which is one of the major metropolitans in East Asia is used as a case study for demonstrating the feasibility of the proposed framework.

3 Data

3.1 Street Network

Taipei street network data were collected from the Institute of Transportation, Ministry of Transportation and Communication, Taiwan. The data contained the street names, types, and the locations. The street types contain national streets (freeway), elevated streets (viaduct), county streets, normal streets, country streets and lanes. This study focus on traffic conditions in the major planar street network, therefore, we filtered out the lanes, which has little influence due to low traffic volumes and elevated streets. There were approximately 5500 street segments in this study (Fig. 2).

To analyze link relationships of street segments, the street network was transformed into a dual graph (Fig. 5). A dual graph (Añez et al. 1996; Rodrigue 2013) or dual representation (Hu et al. 2008; Jiang 2009) has been proposed to illustrate link relationships and it is convenient for expressing turning relationships between streets when turning prohibitions exist in a street network (Añez et al. 1996). This study used a dual graph to form the network, and streets that are always taken as links were converted into nodes and turning movements between streets were converted into edges (Fig. 3). With the streets transformed into nodes, the movements between streets became the links. We also converted an intersection of three or more street segment into edges. For example, street segment A intersected with streets segments B and C and was coded as AB, AC, and AC (Fig. 4a) and then converted into edges AB, BA, AC, and CA (Fig. 4b).

3.2 Traffic Volume

Traffic volume data was provided by the Taipei Traffic Control Center and measured by vehicle detectors (VD). The date of the traffic volume was collected from July 1st to August 31st in 2012. The traffic information was updated every 5 min and the data

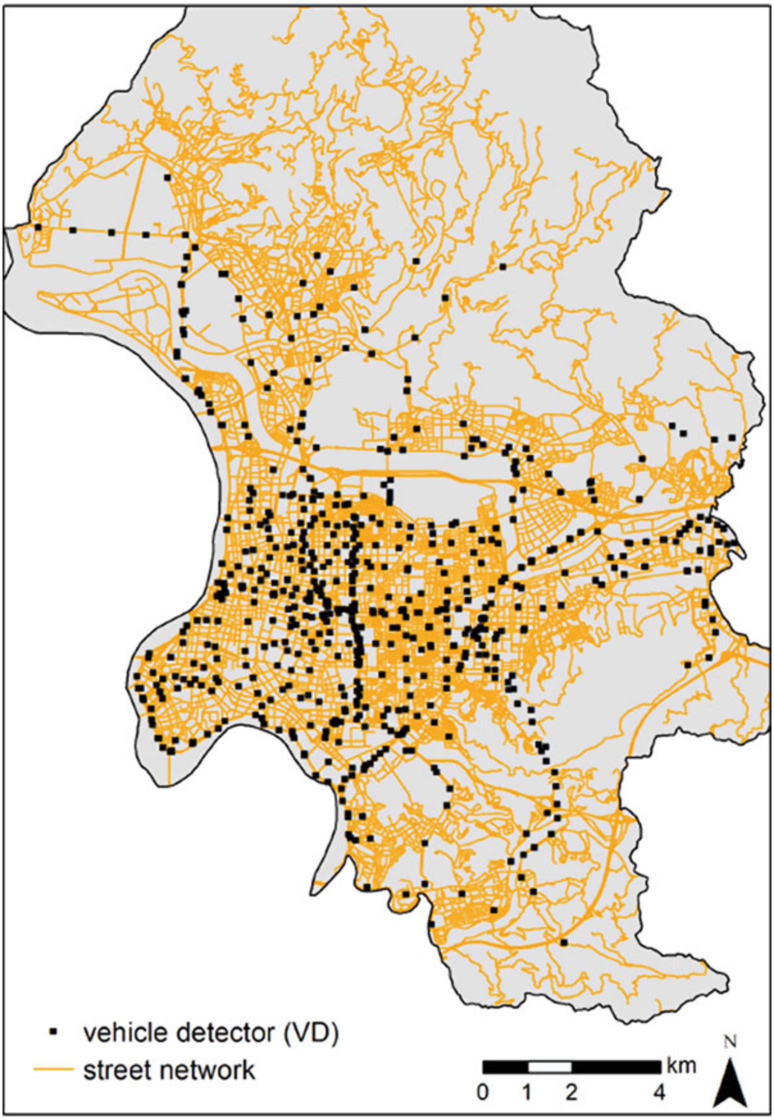


Fig. 2 Street network and spatial distribution of vehicle detectors of Taipei City

items included exchange time, device name (device_id), the name of the location, volume (total_volume), average speed, and the longitude, latitude coordinates of the VD. There are 379 VD are located on different street segments of Taipei City (Fig. 2).

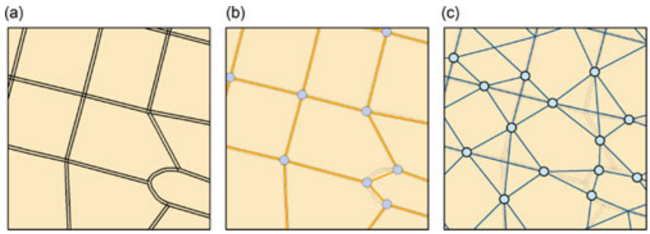
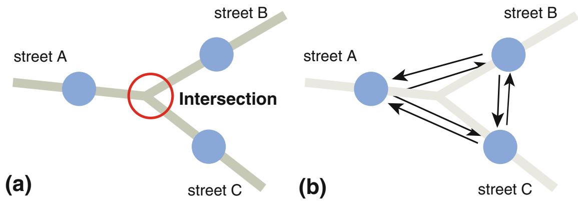


Fig. 3 From street network to dual graph. (**a**) An example street network, (**b**) axial map, (**c**) dual graph

Fig. 4 Illustration of converting an intersection of street segments (**a**) into multiple edges (**b**)



4 Methods

4.1 The Flow-Based Ranking Algorithm

This study proposed a new flow-based ranking algorithm for ranking the significance of street segments, called the Flow-based PageRank (FBPR), which was borrowed from the concept of PageRank (PR). PR is an algorithm used by Google Search Engine (Brin and Page 1998) that uses weighting scores to rank web pages to identify the significant web pages from the enormous and complicated World Wide Web. Two factors make a web page become significance in PageRank algorithm: links from a high number of other pages and links from web pages that themselves have high importance scores. The calculation process of PR can be considered as a continuous process of pages voting for each other. At the beginning, all web pages are assigned the same amount of votes (also called scores); then, web pages pass their own scores to outgoing link-neighbors. The voting process is similar to the flow of vehicles into and out of a street network. The streets with higher volumes will lead a higher volume onto neighboring streets, and streets with more connections will have a higher volume.

However, some settings in PageRank do not correspond to the structure of street networks. For example, PageRank assumes that people move randomly between web pages, and thus the weights of all links are equal. But, human movement is not completely random, and it is influenced by both network structure and individual options (Chin and Wen 2015). Puzis et al. (2013) indicated that network analysis should consider the characteristics of the human movement. Social economic structures and the purpose of trips are often used as variables when simulating movement patterns (Jassbi et al. 2011; Yao et al. 2008). Therefore, PageRank cannot be used directly for street networks (Fig. 5).

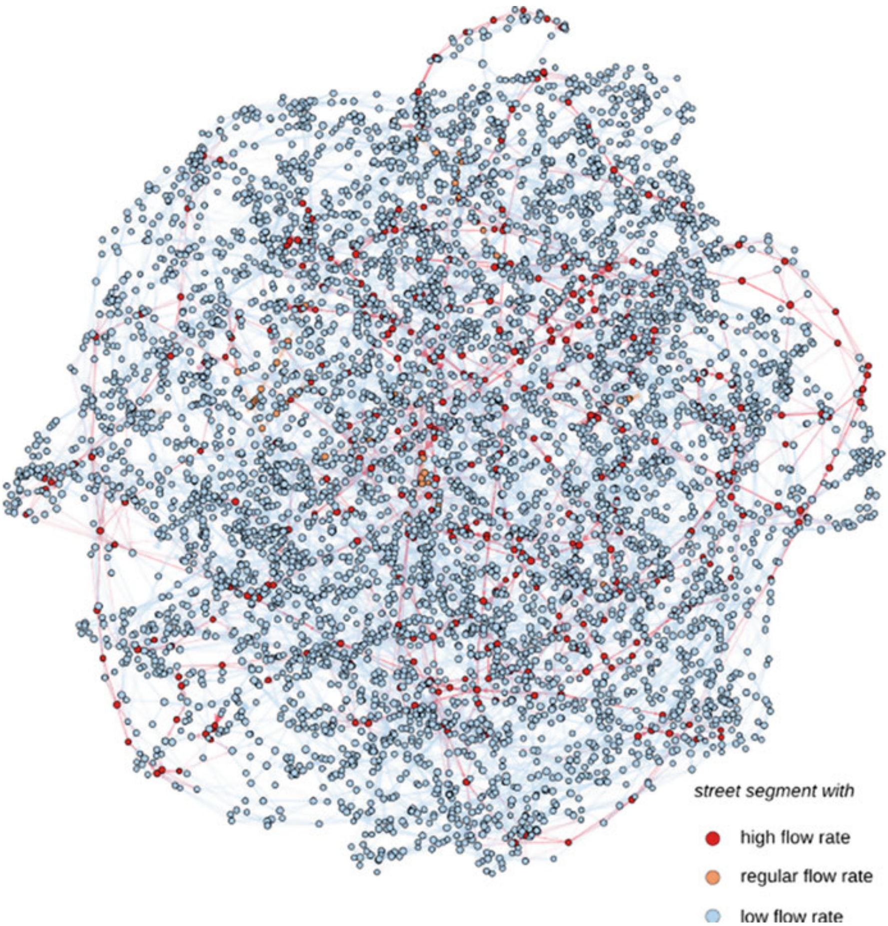


Fig. 5 Dual graph representation of Taipei City street network

Due to the problems mentioned above, the proposed Flow-based PageRank (FBPR) uses a composite index (weight) to replace those variables. The analytical procedure is illustrated in Fig. 6. FBPR uses different weighting schemes to emphasize the attractiveness of streets and decide the distribution of volume between streets (weight of link relationships) (Chin and Wen 2015; Xing and Ghorbani 2004). The weight is termed location attractiveness, which caused by land-use patterns, social economic factors. To correspond to its influence on traffic volumes, real traffic volume data were used to calibrate the attractiveness and link relationships to make the rank of FBPR scores fit the distribution of real traffic volumes. A genetic algorithm was used to determine the optimal values of weights and link relationships.

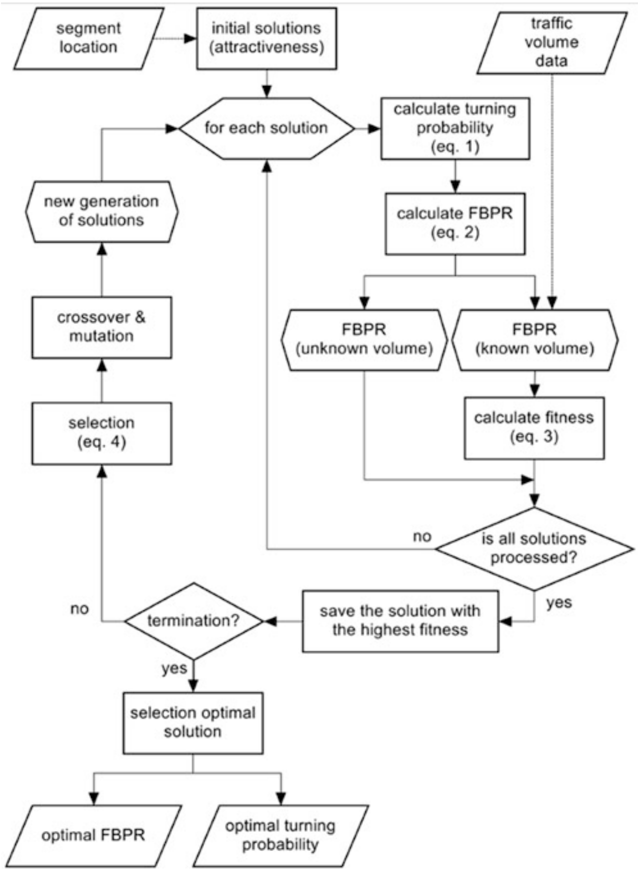


Fig. 6 Analytical procedure of FBPR

4.1.1 Attractiveness of a Node and Link Relationships Between Nodes

Attractiveness is defined as the level of a street segment to attract more traffic flow from neighboring streets. Its value ranges between integers from 1 to 100. The higher attractiveness of a node indicates that a street segment can attract a higher traffic volume from connected streets.

Link relationships were determined by the scores of attractiveness, and FBPR was used to capture link relationships. Equation (1) indicates the transfer proportion of attractiveness from street segment v to u. If $Weight(v, u)$ equals 0.5, then half of the traffic volume on street segment v move to street segment u. The FBPR score of the street segment u is defined by its attractiveness proportion among other outgoing street segments from street segment v, multiplied by the FBPR score of the street segment v in the previous iteration (Eq. (2)).

$$Weight(v,u) = \frac{Attr(u)}{\sum_{p \in R(v)} Attr(p)} \tag{1}$$

$$FBPR_t(u) = \sum_{v \in B_u} FBPR_{t-1}(v) \times Weight(v,u) \tag{2}$$

where: $Weight(v,u)$ is the link weight from street segment v to u; $Attr(u)$ and $Attr(p)$ are the value of the attractiveness of street segment u and p, respectively; $R(v)$ is the set of outgoing nodes of street segment v, which includes street segment u; $FBPR_t(u)$ and $FBPR_{t-1}(v)$ are the FBPR score of street segment u on iteration t, and FBPR score of street segment v on iteration $t-1$, respectively.

The procedure of FBPR was demonstrated in the following example. The sample network is presented in Figs. 7 and 8a. The street segment (A) has three out-

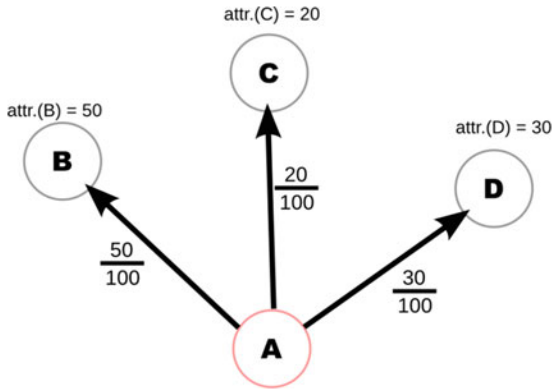
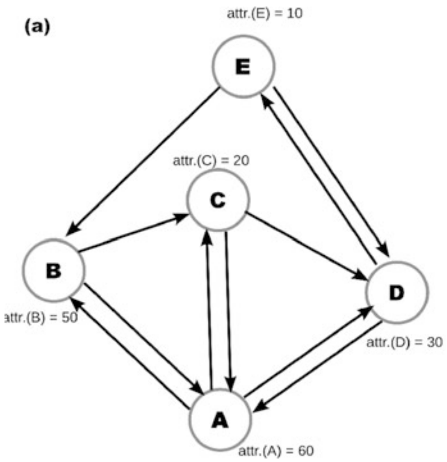


Fig. 7 A partial network including node A and its outgoing nodes, for demonstrating the calculation of the weight from the target nodes' attractiveness



(b)

to \ from	A	B	C	D	E
A	0	6/8	6/9	6/7	0
B	5/10	0	0	0	5/8
C	2/10	2/8	0	0	0
D	3/10	0	3/9	0	3/8
E	0	0	0	1/7	0

Fig. 8 The same network for demonstrating the calculation of the weight matrix from the attractiveness of each node

link neighbors, street segments (B), (C), and (D) (Fig. 7). The $Weight(A,p)$ was determined by attractiveness of the target nodes $Attr(p)$. The attractiveness of nodes (B), (C), and (D) are 50, 20, and 30, respectively. Therefore, the values for $Weight(A,B)$, $Weight(A,C)$, $Weight(A,D)$ are 50/100, 20/100, and 30/100. In the beginning of the process, all nodes received a same scores (there are five nodes in the network, so the initial scores are all $1/5$), and then node (A) distributed 50 % of scores to node (B), 20 % of scores to node (C), and 30 % of scores to node (D). The calculation of transfer proportions within the network is showed in Fig. 8b. The link relationships were determined as the matrix form, which was used as the turning probability in the procedures for calculating outgoing entropy and delineating traffic impact area. The process of transferring scores will repeat until no change occurs in the score of all nodes.

4.1.2 Model Fitting and Parameter Estimation

To capture the real movement along the street network, actual traffic volume data from the VD system is used to calibrate the attractiveness of each street segment. Since, the transfer process described above is similar to the movement behavior in a street network, turning weight can be estimated when the ranking of FBPR scores for each street segment is in agreement with the ranking of actual traffic volume. Therefore, the FBPR model was combined with a genetic algorithm (GA) to identify the optimal distribution of street segment's attractiveness. The fitness function of GA is to maximize the Spearman's Rank correlation among FBPR scores and actual traffic volume (Eq. (3)). If the rank of FBPR scores was highly correlated with the rank of actual traffic volume, the fitness of the candidate solution would be relatively high.

$$fit(s) = \frac{\sum_i (Rank_{FBPR}(i) - \overline{Rank_{FBPR}})(Rank_{volume}(i) - \overline{Rank_{volume}})}{\sigma_{rank\,FBPR}\sigma_{rank\,volume}} \tag{3}$$

where: $fit(s)$ is the fitness of solution s; $Rank_{FBPR}(i)$ is the FBPR rank of node i; $\overline{Rank_{FBPR}}$ is the average FBPR rank of all nodes; $Rank_{volume}(i)$ is the volume rank of node i; $\overline{Rank_{volume}}$ is the average volume rank of all node; $\sigma_{rank\,FBPR}$ and $\sigma_{rank\,volume}$ are the standard deviation of the FBPR ranks and volume ranks, respectively.

GA is an iterative process, which procedures included selection, crossover, and mutation in each iteration. The selection procedure takes fitness as the selecting basis, in which a candidate solution with better performance would have a higher probability of being selected. In this study, the fitness was transformed into relative probability, which represents the probability of each solution being selected from all solutions (Eq. (4)). The selected solution would enter the mating pool for crossover procedure.

$$P(s) = \frac{fit(s)}{\sum_{r=1}^{N} fit(r)} \tag{4}$$

where: $P(s)$ is the probability of the solution s being selected; $fit(s)$ and $fit(s)$ are the fitness of solution s and r, respectively; N is the total number of solutions in one generation.

The crossover procedure in GA chooses two chromosomes as parent solutions from a mating pool and uses the parent solutions to generate child solutions with a certain probability. The multiple-point crossover was selected in this study. Multiple points were randomly selected, and there were 1000 crossover points in the model. The parent chromosomes between two points were swapped, and child chromosomes were generated. For example, solution A and solution B were selected as parent chromosomes, and the attractiveness was swapped between the crossover points, generating a new solution A and solution B. For crossover methods, the crossover rate should be set carefully. The crossover rate was the probability of mating and was set at 0.95. The mutation procedure imitates the phenomenon of natural evolution and maintains diversity in genes. The mutation occurs with a certain probability and generates one or more genes that have no relationship with previous genes. In this study, the GA process iterated for 1000 generations per run before the termination, and then output the optimal solutions.

4.2 The Outgoing Entropy

If most outgoing flows of a street segment is moving toward one street segment, this indicates that the two street segments are forming a major stream of vehicle flow. The existence of major stream suggests that the moving speed of the street segment would be relatively higher. In contrast, if a node's outgoing flow is moving equally toward its outgoing nodes, it represents every vehicle moving along the street segment might take a turn to any direction in the junction, this situation leads to a lower moving speed. The possibility of taking a turn is defined as turning probability. It can be calibrated when fitting the fitness function. Then the entropy of the outgoing flow is used to measure the homogeneity of turning probability of a street segment (Eq. (5)). If the outgoing entropy is high, the outgoing flow is equally divided, and it can reflect low moving speed of the street segment. Hence, the distribution of the outgoing entropy could provide a clear picture of the turning probability and moving speed of the street segments.

$$Entropy(v) = -\sum_{p \in R(v)} (Weight(v,p) \times \ln(Weight(v,p))) \tag{5}$$

where: $Entropy(v)$ is the entropy of street segment v; $Weight(v,p)$ is the link weight from street segment v to p; $R(v)$ is the set of outgoing nodes of street segment v.

4.3 Delineation of Traffic Impact Area

This study used the concept of network modularity to delineate the traffic impact area. The principle of modularity uses the difference between the number of connections inside communities and the number of expected connections to determine the quality of grouping. A higher modularity indicates better grouping. The original modularity was proposed by Newman (2006), but the modularity used in this study is revised by Blondel et al. (2008), also called the Louvain method. The algorithm comprises the iterative two-step procedure: the first step is to group the nodes into different communities and uses Eq. (6) to measure the grouping performance. The second step considers the communities as new nodes, and the links between the communities are converted to the links of the new network. After the new network is formed, the process of the first step is repeated. The node moves to different communities, and the process will repeat until there is no further increase of ΔQ.

$$\Delta Q = \left[\frac{\sum_{in} + k_{i,in}}{2m} - \left(\frac{\sum_{tot} + k_i}{2m} \right)^2 \right] - \left[\frac{\sum_{in}}{2m} - \left(\frac{\sum_{tot}}{2m} \right)^2 - \left(\frac{k_i}{2m} \right)^2 \right] \tag{6}$$

where: ΔQ measured the increasing value of each movement of i; $\sum_{in}$ is the total weight of links inside the destination community; $\sum_{tot}$ is the total weight of links connecting the nodes in the destination community with other communities; $k_{i,in}$ is the weight of links connecting node i with the nodes located inside the destination community; k_i is the weight of links connecting with node i; and m is the sum of the weights of all links in the network.

5 Results and Discussions

5.1 The FBPR Scores

The FBPR scores refer to the tendency of traffic flow concentration. High FBPR score on a street segment indicates more vehicles would flow through the street segment, thus, the flow demand of the street segment is high. Figure 9 shows the distribution of FBPR scores. The result shows that the streets segments with high FBPR scores are concentrated mainly at the center part of Taipei City, which is the location of Taipei's emerging-CBD (the area-A in Fig. 9); the other areas with high FBPR scores are mainly scattering at the western part of Taipei, including the Taipei's old-CBD (the area-B in Fig. 9), and part of the high FBPR score areas are distributed at the corridor area from the western part area towards north (the area-C in Fig. 9). This means these areas, especially the emerging-CBD of Taipei, have a higher demand for traffic volumes and might result in possible traffic congestion problems.

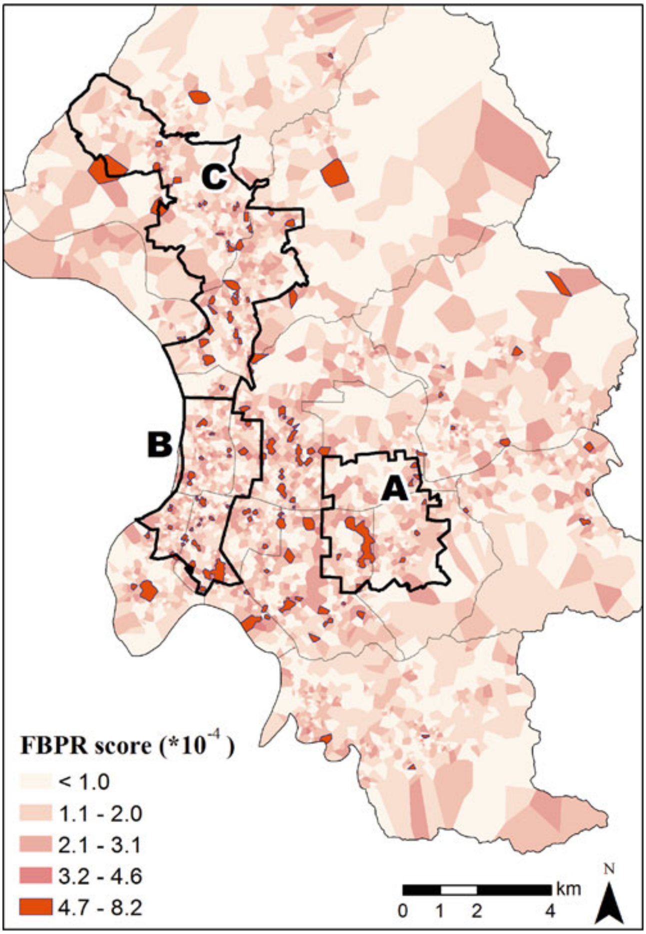


Fig. 9 The FBPR scores distribution in the Thiessen polygon generated by the streets segments (nodes), the emerging-CBD area (*A*), the old-CBD area (*B*), and the corridor bridging the old-CBD and the town located at the north of Taipei City (*C*)

5.2 *The Outgoing Entropy*

The link relationship indicated the turning probability ($Weight(v, p)$) between two street segments, from v to p. Using the link relationship, we calculate the outgoing entropy ($Entropy(v)$) of each street segment, which represent the equality of turning probability. Higher outgoing entropy indicates that the turning probability toward each direction in the junction is more even. Figure 10 displays the spatial distribution of outgoing entropy. Most of the areas with high entropy are located at the old-CBD (the area-B in Fig. 10), the emerging-CBD (the area-A in Fig. 10), the corridor toward the north (the area-C in Fig. 10), and also the transition areas between the

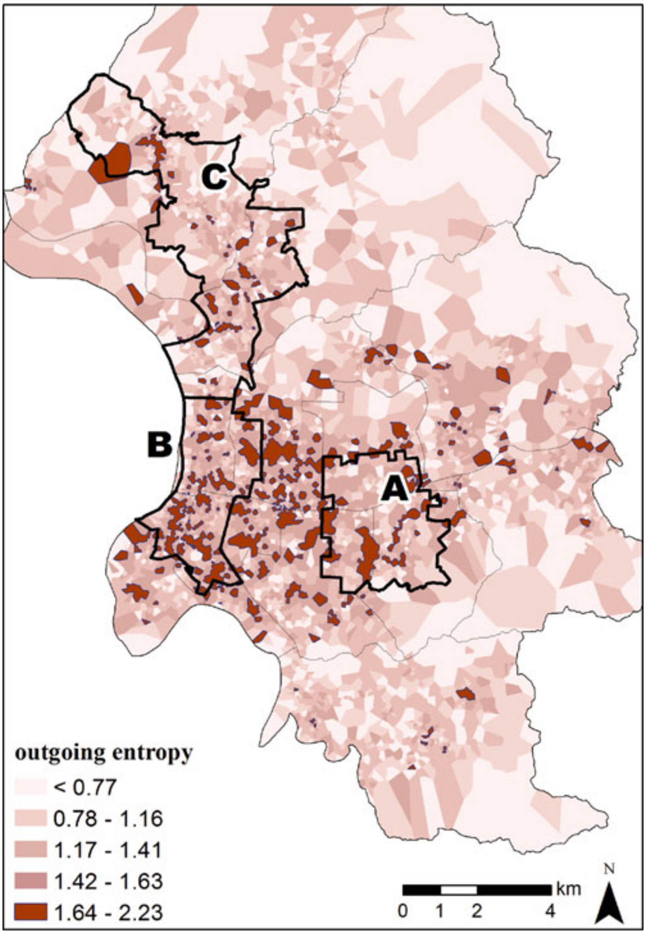


Fig. 10 The outgoing entropy distribution, which is also processed by transforming the entropy index into the Thiessen polygon generated by the streets segments, the emerging-CBD area (*A*), the old-CBD area (*B*), and the corridor bridging the old-CBD and the town located in the north of Taipei City (*C*)

two CBD. This finding suggested that the moving vehicles in the streets at old-CBD areas might turn to different directions from one vehicle to another, and leads to a lower moving speed. This is consistent with the reality since the old-CBD is developed while Taipei City is in its early development stage, and most of the streets were not built for vehicle flows as heavy as today.

5.3 The Congested Segments

Traffic congestion is supposed to have happened at the locations where the traffic flow demand and the complexity are both higher than other places. While the FBPR score could reflect the relative traffic flow demands, and the outgoing entropy could capture the degree of complexity, the streets segments prone to traffic congestion could be identified by overlapping the streets segments with high FBPR score with streets segments with high outgoing entropy, namely the congested segments. We classified FBPR score and outgoing entropy into five levels by using Jenks natural breaks classification (Jenks 1967), which is a data clustering method designed to determine the best arrangement of values into different classes. Jenks natural breaks classification method seeks to minimize the variance within classes and maximize the variance between classes. Then, we used the highest level as the groups of streets segments with the highest indexes. Figure 11 shows the streets segments with highest outgoing entropy, streets segments with highest FBPR score, and their overlapped street segments. The result indicated that although many places at the old-CBD have the highest outgoing entropy, but only some of them are overlapped with the highest FBPR score. This suggested that these streets segments have relatively low traffic flow demands. On the other hand, the streets segments near to the CBD area, some streets segments between the CBD and old-CBD areas, and some streets segments at the southern part of the old-CBD, which have the highest FBPR score, is partially overlapped with the outgoing entropy, suggested that these locations might be easy to get into congestion situation.

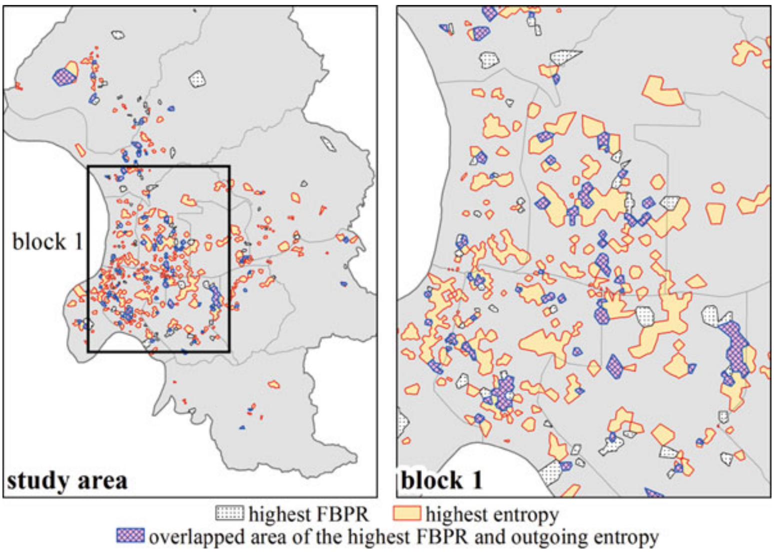


Fig. 11 The streets segments with highest FBPR score, streets segments with highest outgoing entropy, and their overlapped street segments (congested segments)

5.4 Traffic Impact Areas

The community structure algorithm was used to delineate the geographic extents of traffic impact areas. It is interesting to find that some of the boundaries of the traffic impact areas are similar to some of the administrative boundaries. This might be an outcome of the land use zoning, that is decided and planned by the city government. The land use zoning might cause the development of streets system tend to connect with each other within each zone, rather than between zones. The geographic extent of the traffic impact areas are the areas where the within-areas connectivity are stronger than the between areas connectivity.

The segments prone to traffic congestion are compared to the traffic impact areas in Fig. 12. We focused on two of the traffic impact areas in Fig. 12, both areas are located near to the two main railway stations in Taipei City, the Songshan station (block 1) and Taipei station (block 2). Both Songshan and Taipei stations have two types of rail systems, including the intra-city massive rapid transit (MRT) system and the inter-city train railway system. The stations are acting as the hub in terms of transportation connectivity, which implies that the nearby areas would have high transportation needs. In block 1, the traffic impact area (the area for discussion in block 1) has one group of segments prone to traffic congestion, which is near to the Songshan station. This indicated while the congestion occurs at the segments in the group, the congestion situation would probably spread to the northern zone in the traffic impact area. Three groups of segments prone to traffic congestion exist

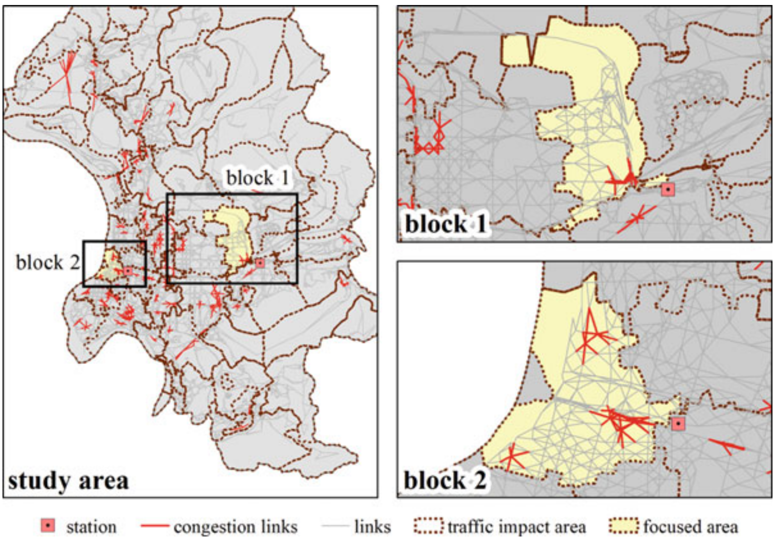


Fig. 12 The traffic impact area, the connected links of the segments with highest-entropy-and-highest-FBPR-score (links of h-h nodes), the other links, and two areas for discussion, which are near to the main stations in Taipei City

in the traffic impact area in block 2. One of them is near to the Taipei station, the other two are the centers of the old communities within the old-CBD. This means that this traffic impact area would get into congestion situation if any one of the three groups of segments has overflowed traffic volume.

6 Conclusions

Identifying characteristics of traffic congestion is currently a crucial issue for urban management. We proposed a new algorithm, FBPR, to determine the turning probability, traffic flow concentration and outgoing entropy for identifying traffic congested segments and impact areas. Only relying on the topological structure of the Taipei City street network, this framework could identify the CBD, and the areas around the stations of the combination of MRT system and train railway system are prone to traffic congestion. The traffic impact areas, which were delineated by the network partition method, could be spatially targeted at priorities of traffic improvement for city planners.

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Logic, Mathematics and Consistency in Literature: Searching for Don Quixote's Place

Javier Montero, Gracia Rodríguez-Caderot, and Pilar Romero

Abstract In this paper we show how uncertainty can be drastically reduced along our linguistic discourse. In particular, after discussing if the analysis of consistency in literature is a legitimate scientific question, from the linguistic analysis of the master piece of Miguel de Cervantes (1547–1616), "Don Quixote of La Mancha", we will propose a procedure to check to what extent the linguistic information provided by the author about the walking speed of Don Quixote within La Mancha is consistent. Such a consistency should allow the existence of a region that meets the author's linguistic description of those trips that involve the place that Cervantes decided not to reveal from the beginning of his book, with the famous sentence "*In a village of La Mancha, the name of which I have no desire to call to mind…*" Taking into account the distances of those trips involving the unknown village and another well located place, and their estimated walking times obtained from a careful reading of such a novel, we will show that those stories seem to be consistent with a more or less constant walking march per day, still assuring the existence of a region within La Mancha that could be reached during the prescribed time for those trips involving the hidden village.

1 Introduction

Modern Societies devote to Mathematics a relevant weight in basic education. Mathematics is widely acknowledged, together with the so-called vehicular Languages. They are basic tools for communication, for understanding the world and for organizing our activities in common. We use to share information by means of words and numbers (but also graphics, pictures, images and videos, which are becoming extremely relevant due to the recent technological revolution). Such an acknowledgement towards Languages and Mathematics has been so deep that, under some circumstances in the history of humanity, access to such knowledge has been limited to people. In fact, it looks like that some associations might

J. Montero (✉) • G. Rodríguez-Caderot • P. Romero
Faculty of Mathematics, Complutense University, Madrid, Spain
e-mail: Javier_Montero@mat.ucm.es; grc@mat.ucm.es; prp@mat.ucm.es

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have overstressed in the past their foundational texts, written in an old language. In this way, those few experts managing such an old language can get in charge of explaining the text, and as a consequence, they become the guardians of such an association. No matter if such a language is any more spoken by people, understanding the seminal message was left in hands of those few experts being able to translate the original words. Something similar might had happened in the past with Mathematics. Knowledge of Mathematics quite often comes with commercial advantages or decisive war technology, and sometimes social advantages. Without Mathematics each long trip might become an adventure with risky return, and certain essential constructions (either from an economic, social or political point of view) were impossible to build up. But leaving aside the key role Mathematics in any technological finding, Mathematics still inspire in part of the Society like a secret flavor. This was the situation with the School of Pythagoras in ancient Greece, where like a sect they did not allow the dissemination of their knowledge.

Part of that vision of Mathematics as an elite can still be found in some modern Societies, and might be behind a dangerous tendency towards a segregated education between Sciences and Humanities. We can still find some friend of ours showing proudness of a lack of basic mathematical abilities. Mathematicians have an important responsibility on this problem, proportional to the presence on Mathematics in basic education curricula. The teaching of Mathematics in basic education is only overcome by the teaching of vehicular Languages. Not surprising since Mathematics is in fact another Language, perhaps the most widely extended Language. No matter the Language the speaker uses in a scientific talk, no matter the specific accent that shows the underlying mother tongue of the speaker, the Mathematics we find are essentially the same. It looks like there is no Science without Mathematics. Without Mathematics our discourse looks imprecise, and with too much imprecision we feel we might being fooled.

There is nothing surprising in the tremendous weight basic education deserves to Languages. Knowledge travels thanks to Languages. Languages play a key role in individual, social and human development. What we know, and how we know what we know, is deeply influenced by our linguistic capacities. The feeling of community is limited by our capacity to share the different visions of others. And the evolution of Humanity cannot be explained without taking into account the development of a Language that allows an intergenerational learning, sharing knowledge throughout space and time.

Still, part of our Society looks to Mathematics as an exclusive knowledge of others, because they do not see how Mathematics affect their lives or their profession. There is a lot of work ahead to explain how Mathematics and Logic are barely needed in every field. An aim deeply connected to the effort of showing the relevance of Science in our daily lives. The scientific approach can be associated to a methodological passion towards facts and rationality, to a continuous call for innovative approaches (Science implies creativeness), and also to an objective acknowledgement of subjectivity (not to be confused with arbitrariness). Everything we say and understand is relativized by our genetic programming, our experiences, the resources of our own language and the way they combine. Altogether they configure our particular view of the world.

Discussion about the presence of Mathematics and Logic in Literature is indeed related to the presence of Science in our lives. Although the term *Science* is in some frameworks associated to *Experimental Sciences*, which stress observation of reality. Observation of reality, in order to be scientific, has to be made according to certain protocols, which pursue to avoid any bias. The existence of these protocols is the true ground of Science. The so-called *objectivity* of Science is reached by means of a team work between scientists, each one trying to prove his or her personal intuition, or simply trying to prove that the experimentation or the argumentation of the other is partially wrong. Success of Science is mainly due to a methodology that shows its efficiency predicting results of future experiments. From the observation of reality, a consistent model or theory is proposed, and should be able to predict yet unobserved behaviours. Quite often such a model or theory is formalized in mathematical terms, or by means of some kind of algorithm or procedure. But no matter the formal technique, such a model assumes a specific Logic, in charge of assuring its consistency, and providing the necessary tools for the management of information. We all assume that reality is consistent (looking for an explanation might imply a search for an underlying Logic). And our models, simplified versions of a complex reality, should capture the essential elements of reality. Including its Logic. That reality has its own Logic, its own laws, is an key hypothesis we make. Knowledge and learning would have no sense without a consistent reality. Then we need an appropriate Logic to build up each model. Better if the Logic we choose for our model fits reality.

Choosing a particular Logic for our model is part of our modeling process. And such a Logic determines how our experiments will be designed, how we will observe reality (we can only see what we have previously decided we can see, while designing the experiment). In this way, what we call *data* cannot be understood as *objective*, once they depend on how we have decided how to observe reality (and scientific methodology will still keep searching for mistakes, inconsistencies and wrong discourses). We can see only those frequencies our eyes are ready to see. Moreover, what we think we have seen has been already processed by our brain. In this way, our brain *sees* continuity in time and space, but such a continuity is not being seen by our eyes. Our eyes only capture a finite number of images per second.

Besides what many people think, Science needs Logic. Consistency of reality is an essential assumption of Science. In other words, we need to assume that reality follows some kind of Logic.

Moreover, we should stress how the objective of Science has evolved, from focussing on a far reality that observer could not in principle modify, to focus its main activity around the Human Being. Health (understood in a wide sense) is capturing increasing funding pursuing the improvement of our life quality, an effort that includes Psychology, Environment, Social Structures and Humanity as a whole. In some way we can say that during the eighteenth Century the top field in Science was Chemistry, that during the nineteenth Century the top field was Physics, and that during the twentieth Century the top field has been Biology. And if the twenty-first Century starts with Health as the top field, most probably the next hot field will be Social Sciences (the increasing impact of social networks in a number of scientific fields might be considered as a clear announcement). But as pointed out in Montero (2009a), becoming the next top field Social Sciences require solving certain paradigm before.

Such a paradigm is the determination of the Logic to be considered for obtaining and processing information in Social Sciences. Many Experimental Scientists consider that Science is made from observation above any other issue. Because they feel that from data everything should follow: from data we produce a theory and the possibility of checking predictions in order to validate such a theory (specifically, that observations are consistent to the theory). Some of those scientists might feel that this process is more or less automatic: artificial reproduction of creativeness is indeed a complex issue, but once a model has been formalized, we should simply follow the rules of *the* Logic. But as already pointed out, the whole process (analysis of alternatives and results, but even the design of the experiment itself) is subject to the Logic we have previously chosen. The problem we realize is that many people only know about one Logic, which is therefore accepted without any discussion. They might be assuming as granted the unique Logic they know about. But as Mark Twain quoted "if all you have is a hammer, everything looks like a nail". Experimental Sciences use to assume the Aristotelian Binary Logic as the only Logic, and in this Logic every assertion must be either true or false. This *crisp* view of reality does not fit very much in many fields within Social Sciences, where concepts use to be naturally poorly defined, and the frontiers between them are not clear. Binary Logic requires that each observation is defined with precision, and each concept either applies or does not apply to every object under consideration. There are no intermediate values *in between* YES and NO. Uncertainty can only appear because I cannot see if there is a YES of a NO, but one and only one of those two possible answers must be true. Neither the question neither the answer escape to such a binary scheme. Probability comes to model uncertainty in this crisp framework. We have to estimate the chances (or the degree of believe) of YES and NO.

It is not till the early twentieth Century when alternative logics to Aristotelian proposal are formalized, showing that degrees of truth are not restricted to the two extreme degrees of truth, TRUE and FALSE. Still, many people do not realize that such a Binary Logic is hard to find in our daily life, where most concepts, commonly associated to words, hold *to some extent*. Most of the concepts in Social Sciences are subject to gradation, a problem that very often is approached by means of Statistics, perhaps by associating the degree of truth to the proportion of people answering YES to certain question. But this probabilistic approach might bring obvious paradoxes: if we have been walking 20 miles from town A to town B, which still is 21 miles ahead, 100 % of us will say that town A is closer than town B. But the truth is that we are *in the middle* of our way (but this answer was not allowed in a question that forced us to choose between A and B as the closest town). Most of the concepts we use in our life are complex and subject to gradation. It is not that our life is full of GREYS because it cannot be explained in terms of BLACK and WHITE: our eyes can see lots of colours, with different intensity, saturation, brightness, … And there is a non-visible spectrum that sometimes is more informative that the visible spectrum our eyes can see.

Fuzzy Logic as proposed by Zadeh (1965) represents a consistent approach for truth gradation, assigning a degree 1 to TRUE and 0 to FALSE, but allowing intermediate values within the unit interval. Although this valuation scale is not the only alternative (see Goguen 1967), fuzzy approach inspires the work developed by Montero (see Parra et al. 2005; Montero 2009b), in order to analyze the possible consistence of Cervantes in his discourse about the hidden place of Don Quixote. The linguistic uncertainty contained in most linguistic discourses, no matter if they are about history or a novel, suggests a tension between ideas and descriptions which is closer to fuzzy logic than to binary logic. At least from a knowledge representation point of view (see Montero and Mendel 1998; Montero et al. 2007 for a discussion about the differences between knowledge representation and decision making approaches).

At this point it is pertinent to bring here the relevance of the recent findings in Neurology and Psychology about how our brain represents information, how this information is managed and how a decision making is finally reached. Many of these advances are related to the linguistic analysis of discourses and images. We take advantage of these advances each time we search on the Web. In fact, one of the hot topics in Science is based upon the increasingly huge amount of information we store. Text analysis and image processing, and in general processing such a mess of digital information, are main issues for the future of modern Society.

Anyway, our discourses use to be consistent enough to allow communication. Despite imprecision, uncertainties and mistakes, our discourses are quite reliable. Because Language is a quite consistent communication system, and the existence of an underlying logic (indeed complex and partially unknown) is the basis for its analysis, modeling and prediction. The ancient myth of Artificial Intelligence talks about robots that cannot be distinguished from human beings. Obviously our discourse can be scientifically studied and mathematically modeled once we capture the essentials of our internal logic. Not only to fully understand our discourses, but to guess our current psychological status or even non conscious thoughts. Or in order to induce in others certain ideas, expectations or feelings. Our current world cannot be understood without the decisive influence of Freud. But it can be neither understood without the impressive rational influence of Science.

Is Literature out of the standard scientific procedures? Is creativity out of any logic? One of the things we most appreciate in the result of a creative process is its consistence, deeply associated to its credibility. Like a theory in any Science, we usually expect that a novel is consistent. It is true that sometimes the artist pursues the surprise by breaking any expected logic, perhaps by means of a sequence of apparently nonsense flashes. But sometimes it is only that we are not able to guess a logic that the author has hidden on purpose.

Don Quixote of La Mancha is a very consistent novel. The story can in general be followed, and the personalities do not behave randomly along the text. Protagonists and places are described in a very consistent way, both to the story itself but also to the reality Cervantes writes about. It is not only that Cervantes writes that he is talking about La Mancha, keeping the real names of existing towns, but that his stories and descriptions are basically consistent to La Mancha. The wonderful work of Ceballos (1965), confirmed by other works, shows the essential coincidence between Cervantes description of vegetation and the true vegetation in La Mancha by those times (see, e.g., Garau 1991; Díaz 1999; Pardo-de-Santayana et al. 2006, but also the classical work of Caballero 1905). The description of La Mancha provided by Cervantes is essentially consistent to La Mancha. Of course we cannot ask for a complete consistency in a novel. Our own description of reality is neither fully consistent. But nobody can discuss the essential consistence between La Mancha and the fiction described in Don Quixote. Moreover, Pollos (1976) has shown the consistent description of Rocinante, Don Quixote's mount, and also the consistent description of Sancho Panza's mount.

"The Lord of the Rings", the master piece of Tolkien, creates a complete world with its languages, amazingly consistent. Several groups of people make different trips and eventually meet. This implies a careful design of adventures in each trip, to assure a credible story. Tolkien gave us the map he had created. But certainly we could have guessed how this map was simply reading the text. Complex stories use to require a provisional structure that can be deleted once the story is finished. Can we get information from a text or discourse? We do it in our daily life conversations. Can we locate a place in a map from a text or discourse? It is kind of surprising to have doubts after Heinrich Shliemann discovering of the Troy of Homer's Odyssey.

Mathematics is basically another language. We continuously translate information of Mathematical nature into our natural Language, and the other way round. There exists a traditional analysis of texts in Social Sciences that have already obtained relevant results, classifying, comparing, structuring and even enhancing a text.

From the consistency of Cervantes book, in this paper we want to stress some methodological aspects to justify the search of Don Quixote's hidden place. Result is consistent with previous research (see again Parra et al. 2005; Montero 2009b), but we will show here its robustness, formalizing hypothesis and therefore its potential weakness. The estimation of the linguistic walking times obtained directly from the text in an independent procedure, still debatable (see Parra et al. 2005; Parra and Fernández-Nieto 2009), clearly points out that the center of the region of Campo de Montiel, in La Mancha. The center of Campo de Montiel can be reached from certain locations consistently to the text, and implying a reasonable mean speed per day, in the terms formalized in this work.

2 Hypothesis to Address the Problem of Finding Don Quixote's Place

Don Quixote's master piece starts with the famous sentence "*In a village of La Mancha, the name of which I have no desire to call to mind . . .* ", and throughout the text Cervantes never gives the name of this town. But he gives the name of certain locations, as the beginning or the end of a trip from or to Don Quixote's hidden place. And from a careful reading of the text the walking time can be estimated, discounting the time he is not walking due to any kind of adventure, always described quite in detail. The complete reading of Don Quixote offers linguistic timings about those trips. Let show some examples:

- In Chapter VII (Part 1), "Of the second sally of our worthy knight Don Quixote of La Mancha": "*Don Quixote decided upon taking the same route and road he had taken on his first journey, that over the Campo de Montiel, which he travelled with less discomfort than on the last occasion, for, as it was early morning and the rays of the sun fell on them obliquely, the heat did not distress them*."
- In Chapter VIII (Part 1), "Of the good fortune which the valiant Don Quixote had in the terrible and undreamt-of adventure of the windmills, with other occurrences worthy to be fitly recorded": "*Finally they passed the night among some trees (. . .). On getting up he tried the bota (. . .). They returned to the road they had set out with, leading to Puerto Lapice, and at three in the afternoon they came in sight of it*."
- In Chapter X (Part 1), "Of the pleasant discourse that passed between Don Quixote and his squire Sancho Panza": "*We must presently go in quest of some castle where we may lodge to-night . . . But anxious to find quarters for the night, they with all dispatch made an end of their poor dry fare, mounted at once, and made haste to reach some habitation before night set in; but daylight and the hope of succeeding in their object failed them close by the huts of some goatherds, so they determined to pass the night there*."
- In Chapter XXXVII (Part 1), "Which treats of the curious discourse Don Quixote delivered on arms and letters": *"and if the worthy gentleman's village is not very far off, I shall be happy if I can do anything for his relief. – It is not more than two days' journey from this, said the curate*."
- In Chapter VII (Part 2), "Of what passed between Don Quixote and his squire, together with other very notable incidents": "*Finally, then, during those 3 days, Don Quixote and Sancho provided themselves with what they considered necessary, and Sancho having pacified his wife, and Don Quixote his niece and housekeeper, at nightfall, unseen by anyone except the bachelor, who thought fit to accompany them half a league out of the village, they set out for El Toboso, . . .*"
- In Chapter VIII (Part 2), "Wherein is related what befell Don Quixote on his way to see his lady Dulcinea del Toboso": "*With these, and other discussions of the same sort, they passed that night and the following day, without anything worth mention happening to them, whereat Don Quixote was not a little dejected; but at length the next day, at daybreak, they descried the great city of El Toboso*."
- In Chapter LXXI (Part 2), "Of what passed between Don Quixote and his squire Sancho on the way to their village": *"And yet it must not be, Sancho my friend," said Don Quixote; "but, to enable thee to recover strength, we must keep it for our own village; for at the latest we shall get there the day after tomorrow."*
- In Chapter LXXII (Part 2), "Of how Don Quixote and Sancho reached their village": "*Evening came, they set out from the village, and after about half a*

league two roads branched off, one leading to Don Quixote's village, the other the road Don Alvaro was to follow ... That day and night they travelled on, nor did anything worth mention happen them, unless it was that in the course of the night Sancho finished off his task."

The objective of the analysis of those linguistic distances should not be the determination of a particular town as Don Quixote's place. Such a precision should not be in principle expected from linguistic distances. The objective of this work is to show that once the walking times are estimated from the text, there is a way to check if there is a region being consistent in speed, taking into account the distances with real locations in La Mancha, and in particular within Campo de Montiel. Walking times, which imply the estimation of the time Don Quixote devotes in each adventure during each trips, were initially estimated in Parra et al. (2005). In such multidisciplinary work that involved a number of specialists from many different fields, a number of variables describing Don Quixote's place were stressed and checked for each town within Campo de Montiel in La Mancha, one of them the estimation of walking times. Such estimation was made by an independent group of specialized researchers. From a mathematical point of view, we simply pretend to show that the whole available information and estimations are consistent with the idea of Cervantes thinking in a Don Quixote walking at a more or less fixed number of kilometers per day, being feasible such a walking speed. The analysis of the text provided several trips between Don Quixote's place and certain locations.

The set of hypothesis for our model are now stated.

2.1 Estimation of Walking Times in Trips Involving Don Quixote's Place (See Parra et al. 2005; Parra and Fernández-Nieto 2009)

– Trip from Sierra Morena: the exact location (Venta de Hiruela) is quite precisely determined, being very close to a place called Venta de Cárdenas, and the walking time to Don Quixote's place is explicitly stated in Cervantes text, two walking days (see Parra et al. 2005). This trip is part of a longer trip to Jándula (Part I, Chapters 10, 31 and 37), around 3.5 walking days, but information from a shorter trip seems to be more reliable.
– Trip to Puerto Lápice (Part I, Chapters 7 to 10): the exact location is also quite precise (2 or 3 km before reaching Puerto Lápice), and the text provides according to Parra et al. (2005), revised in Parra and Fernández-Nieto (2009), to a walking distance of 2.4 days.
– Trip to El Toboso (Part II, Chapters 7 and 8): location is precise and walking time was initially estimated in 2.5 days (Parra et al. 2005), later revised to 2.8 walking days in Parra and Fernández-Nieto (2009), reflecting a potential difficulty in estimating with precision such walking time.

– Trip to the meeting place of Don Quixote and Don Álvaro de Tarfe: in Parra et al. (2005) this place was located at Munera, two walking days also. But in Parra and Fernández-Nieto (2009) the reliability of this location is discussed, so it shall not be considered in this work (nevertheless, in a future analysis of consistency we should also be checking that there exists a place fulfilling the requirements of this meeting place, otherwise global consistency might be lost).

In this way, reliability of the information about locations and walking times is variable: Venta de Cárdenas with its two walking days and location is quite precise. Location of Puerto Lápice is also quite precise, and its walking time seems to be not problematic (around 2.4 walking days). El Toboso is also precise in its location, but the text seems to show more variability (between 2.4 and 2.8 walking days). Munera can be discarded at this stage.

2.2 Estimation of the Distances Between Venta de Cárdenas, Puerto Lápice and El Toboso to Each Town in Campo de Montiel. Several Approaches Can Be Offered

– In Parra et al. (2005), see Table 1, aerial (linear) distances were obtained from a road map, and from these estimations it was concluded that the center of Campo de Montiel was a consistent solution of the system.
– In Rodríguez-Espinosa and Bosque (2009), see Table 2, they used a 1:50,000 cartography of the past Minister of Agriculture in Spain, in raster format, by digitalizing the network of paths and roads within Campo de Montiel and Venta de Cárdenas, Puerto Lapice, El Toboso and Munera. Moreover, they took a Digital Elevation Model (DEM) of the region, also in raster format, with a spatial resolution of 40×40 m. By means of the IDRISI software they estimated the optimal paths (the shorter paths taking into account a selected network of paths) connecting those four coordinates and each town in Campo de Montiel. They even estimated the slope difficulties of each one of the obtained optimal paths.
– Alternatively, in this paper we use quality geographic information from the Geographical National Institute geoportal, www.idee.es (*Infraestructura de Datos Espaciales de España*), within the framework of the Infrastructure for Spatial Information in Europe Directive (INSPIRE, 2007). In particular, the following procedure is applied:

1. Identification of initial data. From the Geographical Data Base (GDB) at 1:200,000 scale (40 m resolution), we select the files with vectorial information, in shape format, for the provinces of Toledo, Ciudad Real and Albacete. Initially, the Geospatial Information of the area of study is stored in the ETRS89 Geodetic Reference System.

Table 1 Map and GIS linear distances

Road map linear distances (Parra et al. 2005) and GIS linear distances	Venta de Cárdenas (map)	Venta de Cárdenas (GIS)	Puerto Lápice (map)	Puerto Lápice (GIS)	El Toboso (map)	El Toboso (GIS)
Albadalejo	64.94	63.89	94.82	97.82	101.37	101.20
Alcubillas	48.87	49.07	67.32	70.03	85.86	85.38
Alhambra	66.41	65.99	56.64	60.15	68.57	68.79
Almedina	52.84	52.69	87.73	89.90	99.97	98.83
Cañamares	75.17	74.40	88.75	90.44	90.17	88.51
Carrizosa	64.50	64.43	66.03	68.40	75.5	75.01
Castellar de Santiago	22.91	23.40	86.74	88.70	111.85	111.03
Cózar	45.79	45.54	79.82	82.01	96.35	95.56
Fuenllana	60.52	60.24	75.20	77.72	85.19	84.48
Membrilla	61.85	62.18	45.21	47.83	67.62	67.45
Montiel	62.41	62.98	38.42	40.95	68.10	67.60
Ossa de Montiel	63.51	63.36	83.94	87.89	91.36	91.72
Puebla del Príncipe	89.33	89.26	71.16	74.94	64.74	64.81
Ruidera	52.15	52.54	93.28	96.75	105.58	105.41
Santa Cruz de Cáñamos	81.25	81.94	61.66	64.46	61.86	60.63
La Solana	60.22	60.34	89.97	93.18	98.71	98.29
Terrinches	62.21	61.11	93.14	96.78	100.91	101.47
Torre de Juan Abad	42.07	42.42	86.61	89.90	103.74	103.57
Torres de Montiel	54.81	55.75	81.27	85.70	93.24	93.50
Torrenueva	26.71	27.76	74.78	76.35	103.03	101.97
Villahermosa	66.42	65.85	79.57	82.62	85.86	85.57
Villamanrique	46.05	46.19	92.33	96.16	107.28	107.64
Villanueva de la Fuente	67.07	76.74	103.37	97.79	109.44	94.89
Villanueva de los Infantes	54.84	54.97	73.61	76.89	86.94	86.70

2. QGIS, a Free and Open Source Software, has been selected for the data modeling process. QGIS enables the transformation of the spatial data into different Reference Systems, as well as the use of vectorial analysis tools.
3. Then, the Universal Transverse Mercator (UTM), a conformal projection in a Cartesian coordinate system, is considered for metric purposes. The transformation to the ETRS89/UTM zone30 is accomplished using QGIS.
4. Using QGIS algebra maps tools, we derive the matrix of linear distances (linear GIS distances with a factor scale of 0.998 for this zone) between each town within Campo de Montiel and the reference locations of Venta de Cárdenas, Puerto Lápice and El Toboso (see Table 1).
5. Finally, we generate facility layers with the projected linear GIS distances derived from the velocity model developed (see below).

Table 2 Optimal path distances

Optimal route distances (Rodríguez-Espinosa and Bosque 2009)	Venta de Cárdenas	Puerto Lápice	El Toboso
Albadalejo	72.80	94.40	106.92
Alcubillas	55.88	66.76	86.64
Alhambra	72.08	64.04	68.72
Almedina	59.28	84.04	99.40
Cañamares	78.96	94.48	102.16
Carrizosa	70.44	72.28	77.20
Castellar de Santiago	30.00	94.48	116.52
Cózar	57.52	77.72	95.72
Fuenllana	71.56	76.36	87.00
Membrilla	74.88	39.44	76.00
Montiel	68.36	84.92	97.44
Ossa de Montiel	98.68	75.08	68.68
Puebla del Príncipe	61.44	90.80	106.16
Ruidera	86.92	65.69	64.64
Santa Cruz de Cáñamos	66.96	90.84	104.40
La Solana	70.44	47.84	66.76
Terrinches	69.64	94.16	107.72
Torre de Juan Abad	49.12	86.04	104.16
Torres de Montiel	66.36	80.32	95.68
Torrenueva	32.64	81.68	103.72
Villahermosa	74.00	83.76	91.44
Villamanrique	55.12	92.08	108.20
Villanueva de la Fuente	82.00	99.48	107.48
Villanueva de los Infantes	66.24	71.48	87.04

Of course, as already stated, once the input is linguistic we should not expect too much precision in our numerical estimation. Determining a specific town from this approach is in principle out of the scope of our study. But we can check if there exists a region being consistent enough with all the information we have. And as happens in standard knowledge process, the accumulation of consistent uncertainties might produce certainty (knowledge is quite often reached by accumulating pieces of poor information each). From this point of view, since there are always several ways to connect locations, we think we should not stress too much any particular route. A global approach based upon linear distances seems more appropriate for detecting regions, although we can take advantage of the detailed study developed in Rodríguez-Espinosa and Bosque (2009), in order to make some natural corrections, in case we find a direct translation between linear distances and optimal path lengths.

Although a systematic analysis of all possible paths is possible, we should anyway take into account that ancient traditional paths could be longer than new paths, and that being Campo de Montiel a quite flat region, shortcuts are always an alternative, as reminded in Parra and Fernández-Nieto (2009). In addition, we should also take into account that in some cases the best option could be the traditional roman roads, some of the now hidden under a modern road or railway lines train.

It should be also noted that all the trips here considered are made around the summer, so the variance of the period with sunlight should not be relevant.

2.3 Estimations of Maximum Speed per Day (See Parra et al. 2005)

– Based upon the work of a veterinarian (Pollos 1976) describing Rocinante and comparing this horse to the donkey of Don Quixote's *squire*, Sancho Panza, in Parra et al. (2005) is was considered that it should be difficult to walk much more than 31 km per day, which more or less implies 10 h of *pleasure* walk of a horse.

But note that more important than the estimation of the maximum speed of Rocinante proposed in Parra et al. (2005) is the fact that an equine veterinarian considers that the physical description of the mounts along the text is consistent. Anyway, the more speed a possible candidate to Don Quixote's place requires, the more tension such a solution brings. And in one moment such a speed will be simply unacceptable. This approach indeed suggests a model in terms of a trapezoidal fuzzy number (see, e.g., Dubois and Prade 1980): a speed around 31 km per day is fine, and the acceptance of the speed decreases in both directions till it is simply unacceptable because it is excessively fast or excessively slow (similar fuzzy number can be built if our speed of reference is modified).

In particular, we are in principle assuming 31 km per day as the reference speed per day. Being aware of the natural uncertainty about the route and the walking rhythm, we accept as consistent an increase up to 20 %, and unacceptable an increase above 30 %. In this way, any mean speed up to 37.2 km per day will be considered consistent, and any mean speed above 40.3 km per day will be unacceptable. A mean speed in between 37.2 and 40.3 is not easy to believe (simply non-consistency).

Anyway, this hypothesis will become less relevant once we assume the next key hypothesis about the uniform mean speed of Rocinante: is there a region that can be reached from Venta de Cárdenas, Puerto Lápice and El Toboso at the same mean speed?

2.4 *Specific Hypothesis: Once We Have Assumed the Locations of Venta de Cárdenas, Puerto Lápice and El Toboso as Reference Locations with Their Respective Estimation of Walking Times (Being Variable in Their Reliabilities), We Consider the Following Hypothesis to Combine*

– We assume that Cervantes planed all those trips within La Mancha having in mind some standard mean speed per day, walking a certain number of kilometers per day, the same for all those trips.

In a future stage we could consider some corrections to take into account the global slope, similarly to the work Rodríguez-Espinosa and Bosque (2009). But La Mancha is a quite flat region and we should not in principle expect high differences in mean slopes, although this should be also checked. In this sense, the region we are looking for should show similar mean speed to Venta de Cárdenas, Puerto Lápice and El Toboso. The key question is to check if from these three locations we can reach some region within La Mancha, in particular within Campo de Montiel as pointed out in Cervantes book, more or less at the same mean speed. If this is not possible, our hypothesis should be rejected.

Moreover, consistently with the above assumption of homogeneous mean speeds, if we reject too fast walking speeds we should also reject too slow walking speeds. Hence, bringing here similar arguments, we should declare unacceptable those mean speeds lower than 21.7 km per days (30 % less than the reference speed), accept those speeds above 24.8 km (20 % less than the reference speed), and declare difficult to believe the middle region.

In other words, we want to check if there is a region in Campo de Montiel that can be reached from the three reference locations at speeds within the interval (24.8, 37.2). If the mean speed to some of those three locations falls outside the interval (21.7, 40.3) that region should be rejected. According to a fuzzy approach (Zadeh 1965), we should be assigning some degree of consistency for each mean speed in both intermediate intervals, (21.7, 24.8) and (37.2, 40.3). But as we will see below, this difficult estimation task appears unnecessary, being able to reach a conclusion simply taking into account the information from the consistent interval and the two unacceptable intervals, fitting in this way the model of rough sets due to Pawlak (1982).

But notice that in case a place can be reached at similar speed from the three coordinates, this fact is relevant no matter the associated speed we used as a reference, being as it is an estimation also subject to discussion.

3 Analysis of Results

The original work of Montero in Parra et al. (2005) was based upon linear distances estimated from a road map. In Montero (2009b) it was stressed that the main objective was to check the consistence of walking distances and the existence of a mean speed more or less the same for all trips, still using the same data considered in 2005. For a critical approach of the original work Parra et al. (2005), see the collection of papers from several authors contained in Parra and Fernández-Nieto (2009).

Besides formalizing the model and its assumptions, in this work we shall give more arguments to stress the robustness of the center of Campo de Montiel as the consistent region, now improving the estimation of distances by means of GIS techniques. In particular, from such a more reliable linear distances, we are going to show that it is almost enough to consider Venta de Cárdenas and Puerto Lápice to point the center of Campo de Montiel as a solution, being the unique region being consistent with El Toboso despite the imprecision about the walking distance of this coordinate. The trip to El Toboso does not provide much discrimination between locations once the information about Venta de Cárdenas and Puerto Lápice has been uploaded, but it is still consistent with the center of Campo de Montiel, and this fact is relevant itself (if El Toboso could not be reached at a similar mean speed, consistency would be lost).

As pointed in Montero and Parra (2015), our hypothesis of a more or less constant mean speed seems particularly natural. We are not trying to guess any sophisticated intention in Cervantes mind, but assuming that he made a plan of the trips in order to avoid potential obvious contradictions that would hit as a consequence the credibility of the whole story. In fact, nobody puts in doubt that Cervantes is in general consistent with La Mancha, despite some details (complete consistency does not exist even in our daily life discourse, and we are talking about a fictitious story). Some populations cannot be a solution for Don Quixote's hidden place simply because they imply an excessive speed per day from one of the coordinates, or a too low speed, or too much variance in those mean speeds. The key issue is if the estimation of linear distances and walking distances can be consistent enough for some region, and if our conclusion can be considered robust enough. In other words, if the above data and estimations are consistent with the hypothesis that Cervantes designs the trips moving Don Quixote within the known map of La Mancha, a map in principle accessible to potential readers.

About the original estimation of linear distances, their estimation in Parra et al. (2005) has received some critics. They were based upon a road map (see Table 1), but Montero (2009b) pointed out that results seemed to be robust enough to support small variations on inputs. The work of Rodríguez-Espinosa and Bosque (2009), determines the optimal paths between each coordinate and all the locations within Campo de Montiel (i.e., the minimal routes taking into account a specific list of existing paths, see Table 2). But notice that our model, based upon linguistic information about waking distances, is not designed to proof that certain town is the solution, but that a consistency region exists. Hence, a general approach based upon linear distances seems more appropriate in our opinion. As already stated, in this paper these linear distances have been estimated as GIS distances on a Cartographic Base, corrected in order to capture the natural higher length of real routes (not the slope). With this objective we take advantage of the work of Rodríguez-Espinosa and Bosque (2009), which will allow us the most appropriate corrections.

Hence, in addition to the GIS distances on the National Cartographic Base, still keeping the original approach based upon linear distances, we shall introduce slight corrections in those linear GIS distances to estimate the length of the possible true route, as shown in Table 1. These corrections are based upon the comparison of mean speeds as estimated from the optimal paths of Rodríguez-Espinosa and Bosque (2009), see also Orden and Viaña (2009), and the new estimation of linear GIS distances. It is extremely interesting to realize that, as can be seen in Table 3, the ratio between those optimal paths and GIS distances is almost constant (we have rounded to 1 some few ratios being slightly lower than 1, a situation that obviously has its cause in natural error measurements). In fact, only three values show a difference above 10 % with respect to the mean for each coordinate, and it will be shown later that these three out of range values will not affect our argumentation (the corresponding locations will be rejected due to another argument, independent for their exceptional ratio behavior).

In this way we are proposing to introduce and ad hoc calibration of the circumferences that in Parra et al. (2005) represented the regions that could be reached from each coordinate at certain speed, now based upon GIS distances, but modified according the following percentages obtained from Table 3:

– Additional 15 % for routes from Venta de Cárdenas.
– Additional 1 % for routes to Puerto Lápice.
– Additional 4 % for routes to El Toboso.

Anyway, we should remind once more that other studies based upon the same parameters of Parra et al. (2005) have reached to similar conclusions, pointing out the center of Campo de Montiel as the most plausible region: besides the work of Rodríguez-Espinosa and Bosque (2009), already cited, see e.g. the probabilistic approach proposed in Girón and Ríos (2008). These approaches could be also developed according to GIS distances (restricting to some list of possible paths of looking for a linear distance).

And we should also stress once again that the decision about which location can be the best candidate to become Don Quixote's mysterious town the population cannot be made solely with this analysis based upon linguistic walking distances. The decision about such a best candidate, once such a walking distances point out a certain consistent region, should be addressed taking into account all possible variables or descriptions that appear in the novel about Don Quixote's place. This was the core of the multidisciplinar team in Parra et al. (2005), which would point towards Villanueva de los Infantes as the location fulfilling a bigger number of those variables. But our objective here is simply to analyze linear and walking distances

Table 3 Ratios between optimal path distances and linear GIS distances

Normalized ratios between optimal route distances and GIS linear distances	Venta de Cárdenas	Puerto Lápice	El Toboso
Albadalejo	1.14	1.00	1.06
Alcubillas	1.14	1.00	1.01
Alhambra	1.09	1.06	1.00
Almedina	1.13	1.00	1.01
Cañamares	1.06	1.04	**1.15**
Carrizosa	1.09	1.06	1.03
Castellar de Santiago	**1.28**	1.07	1.05
Cózar	**1.26**	1.00	1.00
Fuenllana	1.19	1.00	1.03
Membrilla	1.13	1.00	1.00
Montiel	1.19	1.00	1.12
Ossa de Montiel	1.08	1.00	1.06
Puebla del Príncipe	1.11	1.00	1.06
Ruidera	1.17	1.00	1.01
Santa Cruz de Cáñamos	1.06	1.02	1.07
La Solana	1.11	1.00	1.06
Terrinches	1.14	1.00	1.06
Torre de Juan Abad	1.16	1.00	1.01
Torres de Montiel	1.19	1.00	1.02
Torrenueva	1.18	1.07	1.02
Villahermosa	1.12	1.01	1.07
Villamanrique	1.19	1.00	1.01
Villanueva de la Fuente	1.07	1.02	1.13
Villanueva de los Infantes	1.20	1.00	1.00
Mean	*1.15*	*1.01*	*1.04*
Mean − 10 %	*1.03*	*0.91*	*0.94*
Mean + 10 %	*1.26*	*1.12*	*1.15*

Note: Marked in bold those ratios above the 10 % of the mean for each coordinate

to check if there is a region being consistent respect to our hypothesis that the mean speed to the three reference coordinates is more or less the same.

If we look into Tables 4 and 5 we can compare the speeds according to optimal paths (Rodríguez-Espinosa and Bosque 2009) and corrected GIS means based upon GIS linear distances.

And a careful look into Table 6, that shows the differences between maximum and minimum corrected speed considering only Venta de Cárdenas and Puerto Lápice, will confirm that the center of Campo de Montiel can be reached at similar speed (speeds to El Toboso are considered at the walking distances, 2.4 walking days and 2.8 walking days, as respectively proposed in Parra et al. (2005) and Parra and Fernández-Nieto (2009)). Using such difference between the mean speed from

Table 4 Corrected mean speeds

TABLE 4: Corrected GIS mean speed	Venta de Cárdenas +15% (2.0 days)	Puerto Lápice +1% (2.4 days)	El Toboso +4% (2.5 days)	El Toboso +4% (2.8 days)
Albadalejo	36.74	41.17	42.10	37.59
Alcubillas	28.22	29.47	35.52	31.71
Alhambra	37.95	25.31	28.62	25.55
Almedina	30.30	37.83	41.11	36.71
Cañamares	42.78	38.06	36.82	32.87
Carrizosa	37.04	28.79	31.21	27.86
Castellar de Santiago	13.45	37.33	46.19	41.24
Cózar	26.19	34.51	39.75	35.50
Fuenllana	34.64	32.71	35.14	31.38
La Solana	35.75	20.13	28.06	25.05
Membrilla	36.21	17.23	28.12	25.11
Montiel	36.43	36.99	38.16	34.07
Ossa de Montiel	51.33	31.54	26.96	24.07
Puebla del Príncipe	30.21	40.72	43.85	39.15
Ruidera	47.12	27.13	25.22	22.52
Santa Cruz de Cáñamos	34.69	39.21	40.89	36.51
Terrinches	35.14	40.73	42.21	37.69
Torre de Juan Abad	24.39	37.83	43.09	38.47
Torres de Montiel	32.06	36.06	38.90	34.73
Torrenueva	15.96	32.13	42.42	37.88
Villahermosa	37.86	34.77	35.60	31.78
Villamanrique	26.56	40.47	44.78	39.98
Villanueva de la Fuente	44.12	41.15	39.47	35.25
Villanueva de los Infantes	31.61	32.36	36.07	32.20

Note: Marked in blue those speeds within the 20 % range around the 31 km per day, i.e., inside the interval (24.8, 37.2); marked in orange those speeds not within the 30 % range, i.e., outside the interval (21.7, 40.3); marked in yellow those simply non-consistent speeds in between the first region of consistency and the second region of unacceptability. The same code is applied to towns (unacceptable towns in orange, simply non-consistent in yellow and consistent towns in blue); in green those consistent towns with potential conflict in case the walking time to El Toboso is close to 2.5 walking days

Venta de Cárdenas and the mean speed to Puerto Lápice as a measure of consistency, we find the following ranking of solutions:

1. Montiel, with a mean speed of 36.71 km per day and a maximum speed of 36.99 km per day to Puerto Lápice, a little bit below the maximum allowed top level.

Table 5 Mean speeds by optimal paths

Speed by optimal routes (Rodríguez-Espinosa and Bosque 2009)	Venta de Cárdenas (2.4 days)	Puerto Lápice (2.4 days)	El Toboso (2.5 days)	El Toboso (2.8 days)
Albadalejo	36.40	39.33	42.77	38.19
Alcubillas	27.94	27.82	34.66	30.94
Alhambra	36.04	26.68	27.49	24.54
Almedina	29.64	35.02	39.76	35.50
Cañamares	39.48	39.37	40.86	36.49
Carrizosa	35.22	30.12	30.88	27.57
Castellar de Santiago	15.00	39.37	46.61	41.61
Cózar	28.76	32.38	38.29	34.19
Fuenllana	35.78	31.82	34.80	31.07
Membrilla	35.22	19.93	26.70	23.84
Montiel	37.44	16.43	30.40	27.14
Ossa de Montiel	34.18	35.38	38.98	34.80
Puebla del Príncipe	49.34	31.28	27.47	24.53
Ruidera	30.72	37.83	42.46	37.91
Santa Cruz de Cáñamos	43.46	27.37	25.86	23.09
La Solana	33.48	37.85	41.76	37.29
Terrinches	34.82	39.23	43.09	38.47
Torre de Juan Abad	24.56	35.85	41.66	37.20
Torres de Montiel	33.18	33.47	38.27	34.17
Torrenueva	16.32	34.03	41.49	37.04
Villahermosa	37.00	34.90	36.58	32.66
Villamanrique	27.56	38.37	43.28	38.64
Villanueva de la Fuente	41.00	41.45	42.99	38.39
Villanueva de los Infantes	33.12	29.78	34.82	31.09

2. Villanueva de los Infantes, with a mean speed of 32.36 km per day and a maximum speed of 32.36 km per day to Puerto Lápice.
3. Alcubillas, with a mean speed of 28.84 km per day and a maximum speed of 29.47 km per day.
4. Fuenllana, with a mean speed of 33.67 km per day and a maximum speed of 34.64 km per day.
5. Villahermosa, with a mean speed of 36.32 km per day, but a too high maximum speed (37.86 km per day, above the 20 % of the reference speed, 31 km per day).
6. Villanueva de la Fuente, with a mean speed unacceptable (42.64 km per day, above 30 % the reference speed, 31 km per day).
7. Torres de Montiel, with a mean speed of 34.06 km per day and a maximum speed of 36.06 km per day, very close to the maximum allowed top.
8. Albadalejo, with a too high mean speed (38.95 km per day and an unacceptable maximum of 41.17 km per day).

Table 6 Maximum difference between corrected mean speeds

Maximum corrected speed differences	Venta de Cardenas, Puerto Lápice	Mean Speedy	Rank	Venta de Cárdenas, Puerto Lápice plus El Toboso at 2.5 km/day	Rank	Venta de Cárdenas, Puerto Lápice plus El Toboso at 2.8 km/day	Rank
Albadalejo	4.43	38.95	8	5.36	6	4.43	6
Alcubillas	1.26	28.84	3	7.30	11	3.50	4
Alhambra	12.63	31.63	16	12.63	14	12.63	16
Almedina	7.54	34.07	12	10.82	13	7.54	10
Cañamares	4.72	40.42	10	5.96	7	9.91	14
Carrizosa	8.26	32.92	13	8.26	12	9.18	12
Castellar de Santiago	23.87	25.39	24	32.73	24	27.78	24
Cózar	8.33	30.35	14	13.57	15	9.31	13
Fuenllana	1.93	33.67	4	2.43	2	3.26	3
La Solana	15.62	27.94	19	15.62	17	15.62	19
Membrilla	18.98	26.72	21	18.98	20	18.98	20
Montiel	0.55	36.71	1	1.72	1	2.92	2
Ossa de Montiel	19.79	41.43	22	24.37	22	27.25	23
Puebla del Príncipe	10.51	35.46	15	13.64	16	10.51	15
Ruidera	19.99	37.12	23	21.89	21	24.60	22
Santa Cruz de Cáñamos	4.52	36.95	9	6.19	8	4.52	7
Terrinches	5.59	37.93	11	7.07	10	5.59	8
Torre de Juan Abad	13.44	31.11	17	18.69	19	14.08	18
Torres de Montiel	4.01	34.06	7	6.84	9	4.01	5
Torrenueva	16.17	24.04	20	26.46	23	21.92	21
Villahermosa	3.10	36.32	6	3.10	3	6.08	9
Villamanrique	13.91	33.51	18	18.22	18	13.91	17
Villanueva de la Fuente	2.97	42.64	5	4.65	5	8.88	11
Villanueva de los Infantes	0.75	31.98	2	4.46	4	0.75	1

9. Santa Cruz de Cáñamos, with a mean speed of 36.95 km per day, but a too high maximum speed (39.21 km per day).
10. Cañamares, with an unacceptable mean speed (40.42 km per day).
11. Terrinches, with too high mean speed (37.93 km per day) and an unacceptable maximum speed (40.73 km per day).
12. Almedina, with a mean speed of 34.07 km per day, but a too high maximum speed (37.83 km per day).
13. Carrizosa, with a mean speed of 32.92 km per day and maximum speed just below the maximum allowed top (37.04 km per day).
14. Cózar, with a mean speed of 30.35 km per day and a minimum speed of 26.19 km per day, very close to the maximum allowed top.

For all remaining locations, having less homogeneous speeds, we find that some of the speeds are more than 20 % different than the 31 km per day, either because they are too high or too low (Alhambra, Torre de Juan Abad) or even unacceptable (Puebla del Príncipe, Villamanrique, La Solana, Torrenueva, Membrilla, Ruidera, Ossa de Montiel, Castellar de Santiago). Obviously, too high speeds imply more tension than too low speed (we can always walk less kilometers per day, but at some moment increasing speed is simply not possible). But notice that those low speeds we refer to are all of them unacceptable (30 % below the reference speed of 31 km per day). Notice also that incompatibility of Cañamares is due to the speed from Venta de Cárdenas. And Castellar de Santiago is unacceptable because of the speed to El Toboso, under any value within the wide range we are considering, from 2.4 to 2.8 walking days. Moreover, from the 26.19 km per day from Venta de Cárdenas to Cózar (Table 4) we still have margin to increase speed, not falling into inconsistent speed. Anyhow, if we consider any location outside the center of Campo de Montiel, some of the basic parameters to our coordinates (speed or difference of speeds) will fall out of range.

Hence, simply taking into account Venta de Cárdenas and Puerto Lápice we can talk about three groups of solutions, the first one being a clear region within the center of Campo de Montiel:

(a) Montiel (with a maximum speed close to the admisible limit) together with Villanueva de los Infantes, Alcubillas, Fuenllana and, also with maximum speeds close to the admisible limit, Torres de Montiel, Carrizosa and Cózar, in this ranking of homogeneity simply considering Venta de Cárdenas and Puerto Lápice. Montiel, Torres de Montiel and Cózar show tension to El Toboso if we consider 2.5 walking days, but no tension appears if we consider 2.8 walking days.
(b) Villahermosa, Santa Cruz de Cáñamos, Almedina, Alhambra and Torre de Juan Abad, in this ranking of difference between speeds show tension (Santa Cruz de Cáñamos, Almedina and Torre de Juan Abad would be unacceptable with El Toboso only at 2.5 walking days).
(c) Villanueva de la Fuente, Albadalejo, Cañamares, Terrinches, Puebla del Príncipe, Villamanrique, La Solana, Torrenueva, Membrilla, Ossa de Montiel, Ruidera and Castellar de Santiago, in this ranking according to speed differences, but unacceptable with the reference speed of 31 km per day.

In other words, simply taking into account Venta de Cárdenas and Puerto Lápice we are already pointing out the center of Campo de Montiel, in a region around Villanueva de los Infantes, region that is also consistent with any speed within the wide considered range to El Toboso, between 2.5 and 2.8 walking days. Locations outside the center of Campo de Montiel will be discarded as solutions in the moment that the speed to some of the three coordinates (Venta de Cárdenas, Puerto Lápice and El Toboso), is too high, too low or they are too different.

It is important to stress again that although El Toboso does not allow to discriminate within the center of Campo de Montiel, the fact is that it is basically consistent with this region in the range 2.5–2.8 walking days. In Table 4 we see that a number of locations can be rejected no matter the speed to El Toboso we consider within this range: Albadalejo, Castillar de Santiago, Puebla del Príncipe, Torre de Juan Abad, Terrinches, Villahermosa and Villamanrique should be any how discarded. But notice that these locations had been already rejected on the basis of their speeds to Venta de Cárdenas and Puerto Lápice.

In Table 6 we show maximum speed differences considering first Venta de Cárdenas and Puerto Lápice, but also considering both locations plus El Toboso, respectively at 2.5 and 2.8 walking days. Notice the similitude between the ranking without El Toboso and with El Toboso at 2.8 walking days.

4 Conclusions

Meanwhile we accept all the basic hypothesis, from the above arguments we can conclude there exists a region in the center of Campo de Montiel that can be consistently reached at a speed not far from 31 km per day.

The last two figures at the end of this paper allow the visualization of that consistent region (see Figs. 1 and 2). Circumferences correspond to different walking speeds in linear GIS distances, corrected by the estimated factor, which appears to be almost constant for each coordinate of reference (extra 15 % distance for Venta de Cárdenas, extra distance 1 % for Puerto Lápice and extra 4 % distance for El Toboso).

Smallest circumferences in Fig. 1 corresponds to a walking speed of 24.8 km per day. They do not overlap, meaning that there is no compatible region at this walking

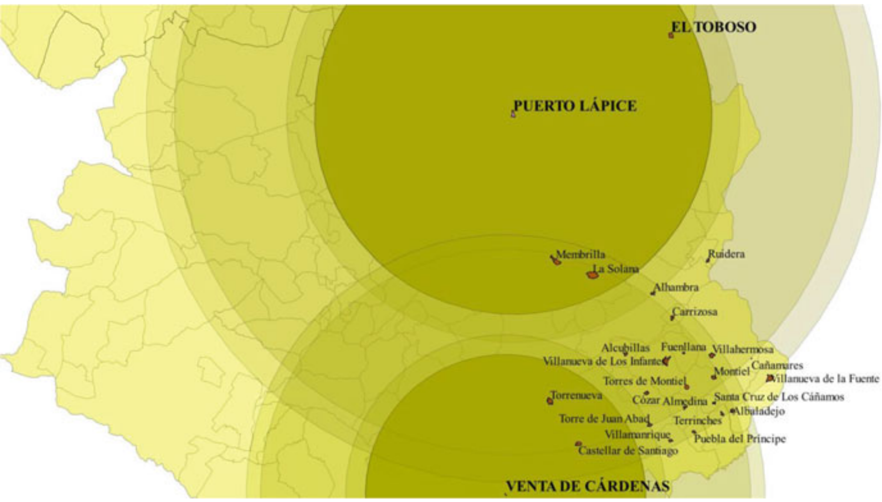

Fig. 1 Consistency regions for Venta de Cárdenas and Puerto Lápice (*wider central rings correspond to the interval of 24.8–37.2 km per walking day*)

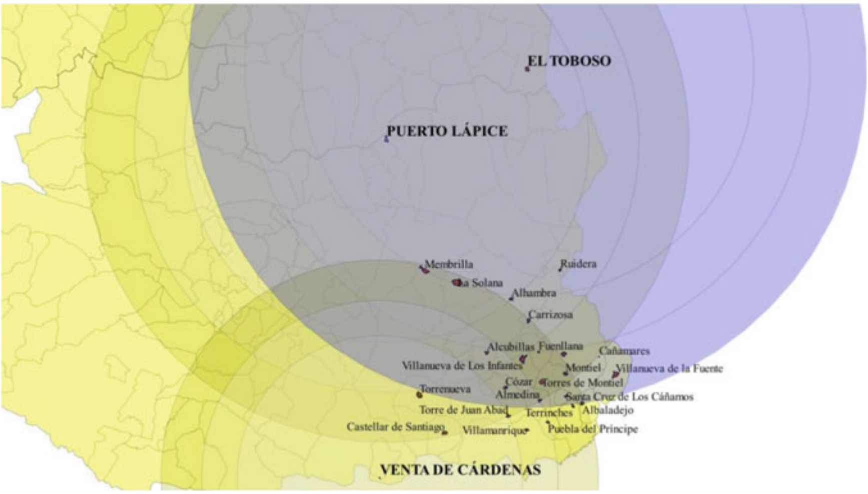

Fig. 2 Consistency region with El Toboso at 2.8 walking days (*central lines in each ring correspond to 31 km per walking day*)

speed. A speed within the interval (24.8, 37.2) marks two potential solutions, one in the center of Campo de Montiel, and another one in the Campo de Calatrava (but from Don Quixote's text we know that the solution must be in the Campo de Montiel).

In Fig. 2 we add the compatibility region for El Toboso at 2.8 walking days, not adding any discrimination within the center of Campo de Montiel, but discarding Campo de Calatrava as a solution. It has no sense, at least from the provided walking distances, to consider any town North to Manzanares, and the central circumferences point to a small region as the most feasible region, Northwest Villanueva de los Infantes. As already stated, more precision than a region should not be expected from our linguistic analysis if distances, but the whole decomposed fiction in Parra et al. (2005) seems to point out to this town as the town that meets more details of the description that Cervantes provides in the text.

Robustness of the obtained results seem enough not to be worried about small estimation errors. In order to invalidate our conclusions we should find relevant mistakes either in Sierra Morena location or in the walking distance to Puerto Lápice (remind that we have accepted a wide enough range from the reference speed, obtained in an absolutely independent research). El Toboso walking days uncertainty does not seem to allow discrimination within Campo de Montiel, but it is important to stress that consistency is kept. If Cervantes would have written his novel not taking into account the true distances to the hidden Don Quixote's place, most probably such a consistency in speed for the three trips would not hold.

These results are basically consistent with the original work in Parra et al. (2005) and Montero (2009b), but also with the optimal routes approach of Rodríguez-Espinosa and Bosque (2009), not considering slope difficulties, and with the probabilistic approach of Girón and Ríos (2008), no matter the variance of the chances each approach suggests for each particular town as a potential Don Quixote's place (please compare Tables 4 and 5).

In this work we have estimated distances between locations as linear GIS distances, which we think is more reliable and robust in order to find a consistent region than the estimations provided in Parra et al. (2005) or the optimal routes found in Rodríguez-Espinosa and Bosque (2009), showing the robustness of the original approach proposed by Montero in Parra et al. (2005) and Montero (2009b). The estimation based upon corrected linear distances does not depend so much on the particular network of paths we consider, showing the consistency of the text with a possible walking speed in mind of the author. If this pattern was not assumed by Cervantes, most probably such a consistent region would not exist, and no place could have been reached at any fixed speed from the three reference coordinates (Venta de Cárdenas, Puerto Lápice and El Toboso).

Of course, each one of the above hypothesis needs to be somehow accepted, starting from the location of the three reference sites, but mainly about the estimated walking times for these three routes. The reference speed (31 km per day), although used in the paper, might not be so relevant, since the most important issue is the speed consistence from Venta de Cárdenas, and to Puerto Lápice and El Toboso: assuming 2.8 walking days to El Toboso, in Table 6 it is shown that Villanueva de los Infantes seems to be the town that can be reached with a smallest difference of distances, followed by Montiel, Fuenllana, Alcubillas and Torres de Montiel (see also Fig. 2). Things change a little bit if we assume 2.5 walking days to El Toboso, implying Montiel, Fuenllana, Villahermosa, Villanueva de Infantes and Villanueva de la Fuente, in this order, as the towns with smallest difference of distance (although Villanueva de la Fuente implies a higher mean speeds). But a consistency region exists for each approach. Nevertheless, it might be relevant to introduce in a future research slope difficulties, as considered in Rodríguez-Espinosa and Bosque (2009), but based upon traditional routes instead of optimal paths (interesting the attempt of Peralta 1944, to walk with a donkey between several towns within La Mancha).

Finally, it is important to stress again that our analysis of linguistic walking distances simply pretends to check it there exists a consistent region. The determination of any specific town within the center of Campo de Montiel implies a different multidisciplinary approach, as the one conducted in Parra et al. (2005), considering as many details as possible about the fictitious complex system described by Cervantes in Don Quixote of La Mancha. Anyway, we have shown how a sequence of linguistic pieces of information can lead to some certainty.

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Energy-Efficient Buildings as Complex Socio-technical Systems: Approaches and Challenges

F. Lachhab, M. Bakhouya, R. Ouladsine, and M. Essaaidi

Abstract On the fast actual demographic trend and increasing comfort level, consumers are becoming more and more demanding in the areas of heating, cooling, ventilation, air conditioning, and lighting. Reducing energy consumption is necessary in all key sectors, such as buildings and construction, cities, and urban areas. Recent studies showed that using Information and Communication Technologies (ICT) will have a significant impact on improving energy efficiency and occupant comfort in complex real buildings. The main aim is to develop energy efficient control approaches and solutions to improve energy efficiency and occupant comfort by using innovative ICT techniques. These solutions could integrate techniques from different domains mainly intelligent control approaches using context-awareness and predictive analytics with a strong focus on occupant expectation, profile, and behavior. In this chapter, we put more emphasis on the influence of occupants' activities, complex building's systems on energy saving by reviewing existing approaches and tools for energy efficiency in complex real buildings.

F. Lachhab (✉)
International University of Rabat, Parc Technopolis, Sala el Jadida 11 100, Morocco

Ecole Nationale Supérieure d'Informatique et d'Analyse des Systèmes, Madinat Al Irfane, Agdal Rabat BP 713, Morocco
e-mail: fadwa.lachhab@uir.ac.ma

M. Bakhouya • R. Ouladsine
International University of Rabat, Parc Technopolis, Sala el Jadida 11 100, Morocco
e-mail: mohamed.bakhouya@uir.ac.ma; radouane.ouladsine@uir.ac.ma

M. Essaaidi
Ecole Nationale Supérieure d'Informatique et d'Analyse des Systèmes, Madinat Al Irfane, Agdal Rabat BP 713, Morocco
e-mail: essaaidi@ieee.org

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1 Introduction

Buildings are responsible for about 40 % of energy consumption and more than 40 % of greenhouse gas emissions (European Commission. Information Society 2010; Ye et al. 2008). With recent products available today, energy consumption in buildings could be cut by up to 70 % (Federal R&D Agenda for Net Zero Energy 2008), but it requires an integrated and collective adaptive framework to show how buildings are operated, maintained and controlled with the support of ICT-based innovation and solutions. Two key areas identified in ICT contribution for energy efficient buildings (The European Commission 2009): (1) ICT can be instrumental in achieving more efficient use of energy through simulation, modeling, analysis, monitoring and visualization tools that are needed to facilitate a "whole building approach" for both design and operated buildings, (2) ICT will also play an essential role in facilitating the implementation of policy and in measuring its effectiveness. The ICT sector can deliver tools that are crucially needed to collect, process, and manage data, and present it in a standardized format. The main aim is to develop energy efficient frameworks to improve energy efficiency by using innovative integrated ICT techniques. These frameworks could integrate technologies from autonomic computing, context-aware computing, machine learning and service-oriented architecture, including context-dependent user expectation and profile. This could be done by including the occupants' actions and behaviors in context tacking into account the complex interlinked elements, situations, processes, and their dynamics. Building occupants might have conflicting interests because of their number and diversity. For example in energy efficient building systems, including occupants activities such as reading, watching, sleeping, could be used to minimize the building energy expenditure.

Energy efficient buildings could be then seen as complex systems composed of different heterogeneous parts or entities (e.g., occupants, computers, robots, agents, sensors, actuator, hardware, software) that interact collectively in complex and largely unpredictable manner. These complex systems should incorporate mechanisms that allow entities interact and perform actions favoring the emergence of global desired behavior. Systems having these features and capabilities are called Socio-technical Collective Adaptive Systems (Barabasi 2013; Coetzee and Eksteen 2011; De Florio et al. 2013; Hardin 1968). In this type of systems, decision-making should be made locally by each entity in a distributed manner and entities might join or leave without disturbing the collective, i.e., the entities should self-organize and continue performing their goals. Furthermore, the system should include decentralized control mechanisms to allow entities with different and conflicting goals to operate at different temporal and spatial scales. In fact, the system could react to the environment changes and buildings occupants' preference with the main aim is to make their life more comfortable according to their locations, current time and situation.

However, engineering these adaptive complex systems require maintaining a strong focus on context-dependent user expectation, profile, and behavior. This could be done by including the occupants' actions and behaviors in context tacking into account the complex interlinked elements, situations, processes, and their dynamics. In this chapter, we put more emphasis on the influence of occupants' activities, complex building's systems on energy saving by reviewing existing control approaches and solutions for energy efficiency in complex real buildings.

The reminder of this chapter is organized as follows. Section 2 provides an overview of control and behavioral approaches for energy efficiency in buildings. In Sect. 3, important metrics used to access approaches and building management systems for energy efficient buildings are presented. Section 4 is dedicated to the presentation of existing tools for evaluating performance metrics of energy efficiency in buildings followed with our ongoing work in this field. Conclusions and perspectives are discussed in Sect. 5.

2 Energy Efficient Building Approaches

Approaches for energy efficient buildings can be classified into two main categories, control and behavioral approaches as presented in the rest of this section (see Figs. 1 and 2) (Lachhab et al. 2015).

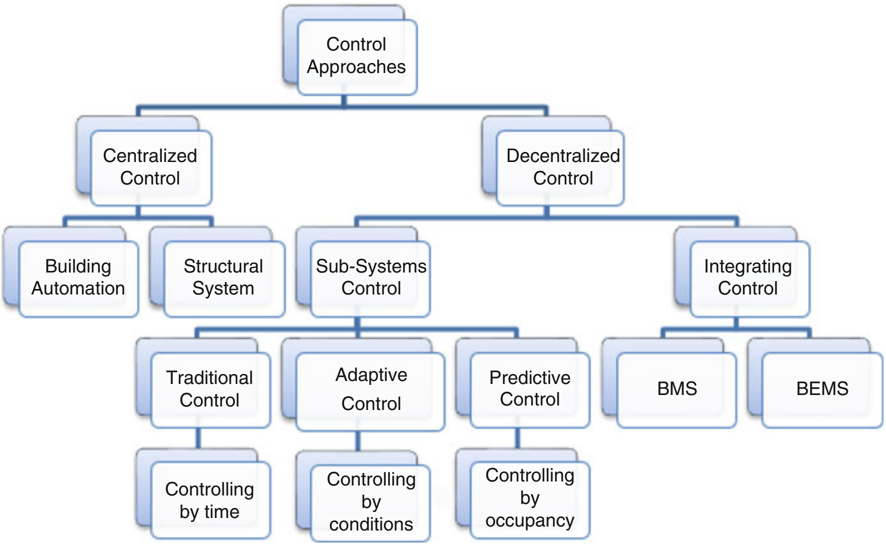

Fig. 1 A classification of control approaches

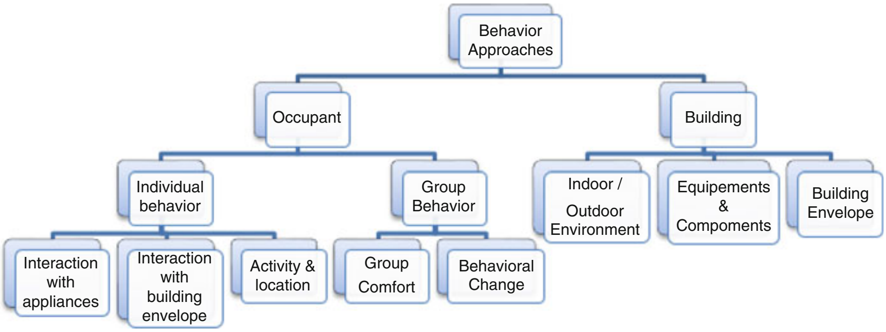

Fig. 2 A classification of behavioral approaches

2.1 *Control Approaches*

The main significant strategy used for improving energy saving is performed by simply installing intelligent controls for managing the operation of all types of building equipment, such as heating and hot water, ventilation, cooling and air conditioning, lighting, windows and shading devices. In fact, a good energy-efficient control strategy is essential within a building to optimize services taking into consideration equipment location and their monitoring. Deploying this type of intelligent control could have a major impact on the performance of building energy services. There are two types of approaches: centralized and decentralized as depicted in Fig. 1.

2.1.1 Centralized Control

Most building control systems currently available on the market are centralized. They rely on a single controller that operates all devices available in a building. A controller of this type usually requires detailed information about all devices and a direct communication channel of each device. In other words, many strategies were implemented as a centralized control in building such as building automation control as well as structural systems approaches. For many years the structural systems approaches were largely used as a structural control of closed loop structures such as energy buildings and construction systems which requires assessment of dynamic response with various structural properties of a building systems as well as building regulations (Adeli and Jiang 2006; Faruque Ali and Ramaswamy 2009; Yang 2001), e.g. Yang (2001) that was proposed as an effective control by resolving a complicated nonlinear behavior and incoherent parameters of structural response under centralized systems. Conversely, the structural system approach requires more optimum control by combining mathematical models with real building response. In other hand, building automation and control systems used to enable a continuous controlling and monitoring of several metrics (e.g. temperature, humidity, CO_2 concentration) inside and outside the building based on many sensors and actuators placed at different locations throughout a building. Nowadays, building automation systems implementations rely largely on wired networks and different standard protocols have been proposed (Mozumdar 2009). Between different protocols, the most used are, EIB or its successor KNX Association (2003), BACNET (2003).

2.1.2 Decentralized Control

Unlike centralized control mechanisms, decentralized control is proposed to substitute the global control system into several local control subsystems. A local control receives local signals at each subsystem and sends control signals to the same subsystem. This control approach tends to be very effective. However, requirements of control optimization and robustness would be desirable, to attend modern power systems demands. Two main control structures using distributed measurements have been proposed in several studies (Berg-Munch et al. 1986; Doukas et al. 2007; Dounis and Caraiscos 2009; Inoue 1998; Lute 2000; Mohsenian-Rad and Leon-Garcia 2010; Nesler 1986; Oldewurtel 2012; Reinhart 2004; Yeh et al. 2010): *sub-system control* and *integrating Control*.

The sub-system control was proposed mainly for better monitoring and control of systems in buildings. This can significantly reduce the building's operation expenses. There are three main types of control used largely in control building services.

- **Control by time**: in order to minimize the energy consumption, prior to 1990, several controls strategies were developed for feedback control of building metrics (e.g. indoor air quality, thermal comfort, energy performance). One of these strategies, On/Off time switches control that was developed to switch services On and Off in response to programmed time sittings such as in lighting control system (Reinhart 2004) and HVAC systems (Berg-Munch et al. 1986). In fact, there are a variety of time switches controls going from a 24-h on/off times (Mohsenian-Rad and Leon-Garcia 2010) to 7-day times, which allow setting up control for specific week days.
- **Control by condition**: this type of control is an extension of controlling services by time, which was proposed as a daytime optimization control to switch service Off during a building occupancy period. In order to use optimal control (Dounis and Caraiscos 2009; Inoue 1998), and adaptive control (Nesler 1986), several approaches have been proposed to provide the self-regulation and self-adaptation ability of services to the climate conditions in the various buildings. More specifically, adaptive controls rely mostly on occupancy controls which are used today in lighting and ventilation service and propose rapid response to the indoor environment. Recently, in Yeh et al. (2010), authors proposed an autonomous light control solution based on occupants' preferences that dynamically adapt to environment changes.
- **Control by occupancy**: building services can be controlled by environmental conditions such as temperature (i.e. for heating, cooling and ventilation systems),

day-lighting (i.e. for lighting and shading systems), humidity (i.e. for ventilation systems and air conditioning systems), and even carbon dioxide levels (i.e. for ventilation systems). Based on these parameters and occupants preferences, a predictive control model (Lute 2000) could improve energy efficiency in buildings by maintaining control of HVAC systems as well as electric lighting and CO_2 centration while respecting occupant comfort. Indeed, among developed models for control prediction, a stochastic Model Predictive Control (MPC) approach was developed in Oldewurtel (2012) and takes into account weather predictions and occupancy behavior to restrict the energy consumption in buildings while maintaining thermal and visual comfort for occupants.

However, better accuracy and improved response can be obtained by combining some of the above control strategies into one smart control. More precisely, in such local controls each subsystem operates autonomously to reach an intelligent control, there is not cooperation between all subsystems. To tackle this issue, integrated controls have been proposed. Each subsystem operates autonomously to reach an intelligent control, but all subsystems can cooperate with each other to gather global information for all subsystems of the building. The more that building sub-systems are integrated, the more efficient the building will be operated. Many control techniques can be combined into a single building energy management system (BMS or BEMS). Indeed, a BEMS was developed in Doukas et al. (2007) as a computer-based energy management system for saving energy in a building by managing energy with intelligent controllers that monitor conditions throughout the building and determine the operation of services in an optimal state and in response to changing conditions levels.

2.2 Behavior Approaches

Recent studies have shown that improving building energy consumption and user comfort could be further enhanced by taking into consideration occupants and building behaviors. Several approaches have been proposed by taking into consideration occupants and building behaviors in order to increase the building performance while maintaining a good occupants comfort level as depicted in Fig. 2.

2.2.1 Building Behavior

Three main control techniques taking into consideration the building behavior have been proposed: *building envelope*, *building equipment*, and *building indoor and outdoor environment*. Most techniques carry out building envelope characteristics to improve more efficiency on building usage, which control the quality of the indoor and outdoor environments of a building. While HVAC systems and electric lighting are categorized as active strategies, building envelope elements can be classified under passive strategies because it depend on climatic factors (Sadineni et al. 2011). The building envelope can provide additional improvement of building performance by determining energy requirements in several components such as walls, roofs, fenestrations, thermal insulation, ceilings and thermal mass. In fact, several studies have been performed to define the impact of building envelope on building energy usage. For example, in Tuhus-Dubrow and Krarti (2010) authors improved thermal comfort and reduction in energy consumption by developing a simulation and optimization tool that couples a genetic algorithm to a whole-building energy simulation engine to select optimal values of a comprehensive list of parameters associated within the building envelope.

Furthermore, building services such as the HVAC, supply and exchange air either naturally from outdoor and indoor space. Therefore, inadequate maintenance of HVAC systems is one of the main problems that influences the building indoor environment and systematically impacts on occupants comfort. In ISO 7730 (2005), Yao (2009), El Mankibi (2009), Atthajariyakul (2004) authors have developed approaches to enhance thermal comfort and indoor environment quality by calculating CO_2 concentration, carbon emissions embedded in materials and proposed adaptive models for air management in buildings. A dynamic model is presented in Kim and Kim (2010) and shows that optimal daylighting systems can provide adequate visual comfort and can save energy if they are carefully designed.

Building equipment and components, such as HVAC and electrical lighting, are also main important elements in building that must be controlled to save energy. Furthermore, occupant's interactions with building equipment lead to conserve the environmental comfort of each occupant by taking into consideration preferences and schedules. Several studies show that predicting the probability of an occupant interactions with these services could allow managing in real time the performance of energy use. Next section illustrates some examples of approaches that take into consideration occupant behavior.

2.2.2 Occupant Behavior

There is a fundamental need to include behavior and social dimensions as important factors that contribute towards indoor environmental comfort and reduction of building's energy consumption. The ability of the occupants to make their own choices, adapt their indoor environment with their alterations to operable services (i.e. interaction with several materials such as windows and window shading devices, lights, fans, carpets, and thermostats) and to control their direct environment is critical to their satisfaction as end users. Various studies have been dedicated to this topic by analyzing occupants' behavior and interactions through the building (Azar and Menassa 2011; Fabi et al. 2012; Hoes et al. 2009; Nguyen and Aiello 2013; Oldewurtel et al. 2013). These studies can be classified into two main categories based of occupant modeling approach used as represented in Fig. 3.

Individual Behavior models include occupants' interactions with appliances and building envelope, occupant presence and activities. Occupant presence and behavior in buildings has been shown to have large impacts on space HVAC services demand, energy consumption of lighting and space appliances, and building controls (Nguyen and Aiello 2013). Several stochastic behavior models have been developed

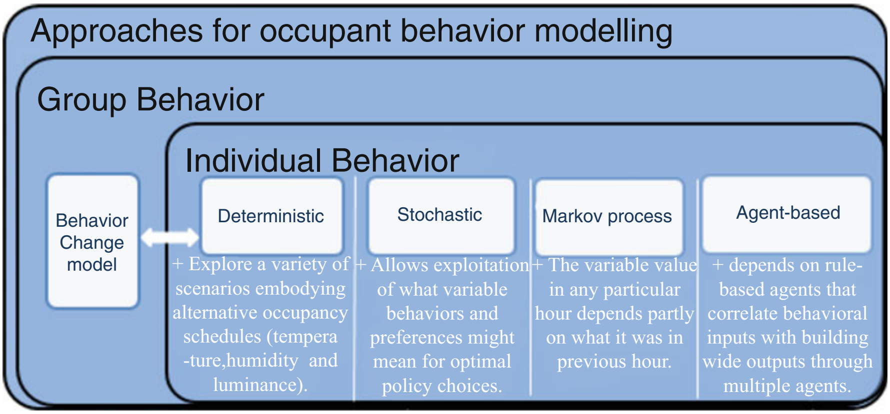

Fig. 3 A classification of behavior approaches based on occupant models

to model individual behavior of occupant, such as presence and interaction with space appliances and equipment, in order to understand the occupant interactions with the indoor environment. Several models have been developed through providing occupant behavior awareness, such as Markov chains, in modeling random opening of windows by occupants (Fabi et al. 2012), and stochastic model applied Poisson distributions to generate daily occupancy profile in a distinct occupied office, based on an occupancy model and dynamic daylight application. The aim was to compute annual energy demand for electrical lighting (Reinhart 2004). For example, in Oldewurtel et al. (2013), authors propose a model by identifying general patterns of occupant behaviors as a function of visual comfort metrics, such as illuminance and irradiance. However, most of the previous occupancy presence models were tested on an individual occupant. Authors in Azar and Menassa (2011) have developed a generalized stochastic model for the simulation of occupant presence with derived probability distributions based on Markov chains. Recently, researchers explore artificial intelligence approaches (e.g., machine learning) that associate behavioral occupant inputs with building services outputs and model them as an agent-based system. In this model individual occupant are represented as an autonomous agent with unique personal states and behavior patterns, as well as rules of interacting with building appliances and equipment. Between numerous solutions of agent-based models that have been developed to understand individual occupant behavior, there is a large use of BDI model based on human attitudes of Belief, Desire, and Intention.

Recent studies have shown the conflictual behavior in a group of occupants in a building. Therefore, modeling different occupants' behavior and their interaction with others and their neighboring environment is required. Since agents can communicate and coordinate with each other as well as with their environment, most of proposed approaches show that agent-based modeling approaches are adequate to models complex and behavior change problems. For example, an integrated model was developed in Hoes et al. (2009) using ESP-r to intelligently assess the sensitivity of performance indicators for the complex user's behaviors while maximizing their satisfaction. Main performance metrics used to assess developed approaches as well as building energy management systems are described in next section.

3 Energy Efficiency Metrics in Buildings

There are mainly two main categories of metrics to measure energy efficient buildings (see Fig. 4): (1) improving the building performance by taking into account all energy sources and the carbon dioxide emission factors, and (2) reaching the occupant comfort while minimizing negative environmental impacts and ensuring building safety. These metrics need to be considered for developing holistic frameworks for minimizing energy consumption while improving occupant comfort.

3.1 Performance Metrics

Performance metrics are required to evaluate the energy efficiency in buildings. There are two main important metrics, the first metric is the ability to improve the efficiency of energy by reducing and managing energy demands and the second one is the control of building systems by managing in real time energy expenditure. Currently, the efficiency of energy sources tends to provide long-term benefits by

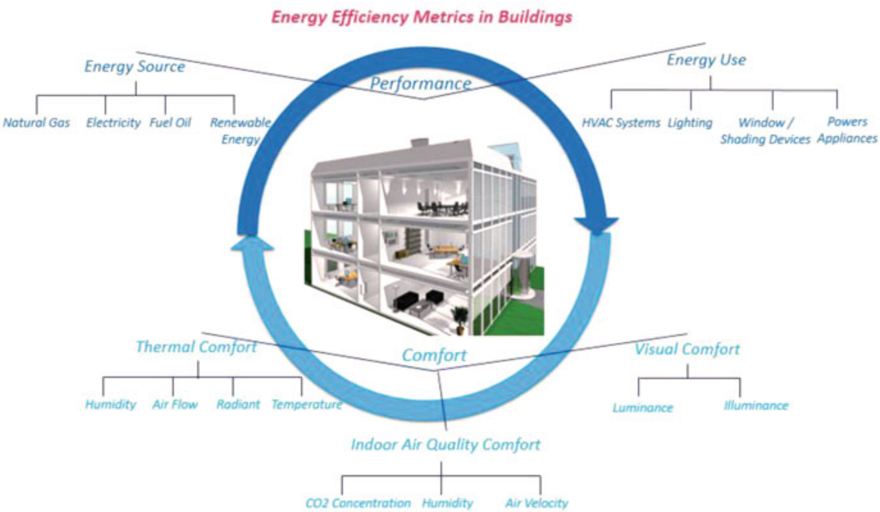

Fig. 4 Energy efficiency metrics for buildings (Lachhab et al. 2015)

lowering base load (e.g. Electricity, Natural Gas, and Fuel Oil) and peak demand. Beside the use of a passive energy sources there is a need for additional generation and transmission assets to achieve “zero-energy”, using renewable energy sources (e.g. solar, wind). This could lead to more efficiency in reducing energy consumption and cost savings. Furthermore, high performance of a building will be only achieved if there are various control strategies implemented in buildings to enhance the management of energy use. This includes, the control of HVAC systems, lighting and power appliances in buildings. Indeed, several control strategies were developed for managing the operation of all types of building equipment as presented in the previous section. For example, cyber-enabled BEMS meant to increase energy utilization efficiency by decision-making control methodology using agent-based systems for electrical, heating, and cooling energy zones with combined heat and power system optimizations (Zhao 2013).

3.2 Comfort Metrics

Comfort metrics can be categorized into three main metrics: *thermal comfort*, *visual comfort*, and *indoor air quality comfort. Thermal comfort* is an important metric for indoor environment quality and also one of the main sources of energy consumption in buildings. Maintaining occupants’ thermal comfort means conserving the performance of thermal parameters (temperature, mean radiant sources, air flow velocity, and humidity) within an acceptable range. This means that the thermal comfort depends firstly on heating, ventilation air conditioning management services and the insulation of buildings. Thermal comfort evolution methodologies use respectively two keys calculation: the analytic theory by the ISO 7730 (2005), and the extended Standard Prediction Mean Value (adaptive PMV) (Yao 2009) model for non-air conditioned buildings. The adaptive PVM model uses adaptive factors that affect the sense of thermal comfort, which is calculated using physical measurements for warm and cool conditions. Many research works combine numerical local weather forecasting and MPC (Model Predictive Control) to enhance building energy usage and indoor thermal comfort. In other words, these static and adaptive thermal approaches are mainly used to assess thermal comfort in buildings.

Visual Comfort depends primarily on lighting conditions of a building (luminance, illuminance). Maintaining visual comfort means ensuring that people have enough light to perform their activities, i.e., the light has the right quality and balance, and people have good views. Several occupant behavior models utilize predictions of visual comfort such us DGP-based shading control (Reinhart and Wienold 2011), which uses the concept of daylight by taking into account different assessment modes, such as sky conditions, blinds setting and sensors positions, to predict the short-time-step development of indoor illuminance. In Reinhart (2004) a manual lighting and blind control algorithm was developed to predict electric lighting usage based on probabilistic behavioral patterns, which have all been observed in actual office buildings. In fact, an extended DGP control method—

the Adaptive Zone (Jakubiec and Reinhart 2012)—was proposed to add occupant's preferences, where the occupant has the right to change the view direction to avoid the discomfort in workspace. However, ensuring acceptable level of visual comfort involves management of lightning and directly affects the energy consumption of the building.

Indoor air quality is a significant concern in maintaining occupant comfort in buildings. More precisely, the air quality of the indoor environment can profoundly affect the health, comfort, and productivity of building occupants. It is important to evaluate the air quality according to the level of CO_2 concentration, and identify if the air is clean, fresh and circulated effectively (i.e. verify air velocity distribution within and between rooms in building). The building sector currently contributes approximately one-thirds of energy-related CO_2 emissions worldwide, it is economically possible to achieve a 30 % reduction by reducing CO_2 emissions (Ürge-Vorsatz et al. 2007). Currently, the CO_2 emissions depend not only on the energy consumption in systems (i.e. heating, cooling and hot water), but also on the building envelope, the occupant behavior and the type of energy sources used (Salat 2009). Some studies have shown that the carbon dioxide concentration is considered as a relevant key according to occupants' perception of indoor air quality. For example, relationships between the percentage of user discomfort with indoor air quality and calculated levels of CO_2 concentration are proposed in Seppänen et al. (1999), Berg-Munch et al. (1986). Recently, in an experimental study (El Mankibi 2009), authors show that the level of occupancy affects negatively the indoor air quality using the concentration of carbon dioxide as an evaluated index. On the other hand, several studies stated that perceiving indoor air quality is related to an intelligent maintenance of HVAC systems (i.e. adopting active systems such as HVAC fans and ducts in control approaches). In Atthajariyakul (2004), a multi-objective optimization with gradient-based method is implemented to yield optimal indoor-air condition in order to insure thermal comfort and indoor-air quality while maintaining efficient energy usage.

Table 1 summarizes various factors that play an important role for energy consumption and occupant comfort in energy efficient buildings: physical properties (e.g., geography, building type, location), equipment (e.g., heating, ventilation and air-conditioning system, auxiliary production of electricity or hot water), outdoor environment (i.e., weather condition), and occupants' behavior and activities (e.g., reading, eating, watching TV).

4 Modeling and Simulation Tools and BEMS Platforms

In previous sections, we mainly highlighted approaches that aim to deliver, implement and optimize building concepts to significantly reduce energy consumption and CO_2 emissions. Most approaches use simulations to assess the performance of buildings taking into consideration only a part of today's buildings. In fact, energy efficient buildings are complex systems composed of different heterogeneous parts

Table 1 Requirements and metrics

	Efficiency metrics		Comfort metrics		
Requirements	Energy sources	Energy usage	Thermal	Visual	Air quality
Building physical properties	Solar	×	Thermal insulation and mass	Building type	Geography and building type
Equipment control	Electricity	Powers appliances	Heating and ventilation systems	Lighting and shading systems	Air-conditioning systems
Outdoor environment	Wind	Relative humidity	Weather condition	×	Air velocity
Occupant behavior	×	Interaction with building systems	Surface temperature preferences	Inadequate luminance	CO_2 concentration levels

or entities that could interact collectively in complex and largely unpredictable manner. The system requires an integrated and a holistic framework that includes decentralized control mechanisms to allow entities with different and conflicting goals to operate at different temporal and spatial scales to the environment changes and buildings occupants' preferences and activities.

However, no single simulation tool or mathematical model provides all capabilities and features to analyze the whole building in terms of efficiency and comfort metrics. For example, two different approaches can be distinguished for modeling and evaluating the performance of buildings: white-Box models that are based on physical properties and black-Box models that are non-physical models based on statistical/stochastic relations. Hybrid forms of the two approaches are usually called Gray-Box models. While all these models are appropriate for failure detection, for failure diagnosis and optimization purposes, the consideration of physical parameters is indispensable. Mathematical models have been, however, developed to simulate the energy consumption of buildings. Several software tools provide the necessary mathematical background for such simulations (e.g. Modelica, Matlab). The main benefit of such models is that it allows studying in depth the behavior of physical structures under predictable and well defined situations and procedures. For example, "Modelica" is becoming a standard for computational science and engineering for innovative building energy modeling and control systems. It is built only to analyze novel energy and control systems. However, efforts have been done so far focused mainly on simulating the performance of new systems, such as new HVAC architectures to study the energy consumption based on the actual context. In the case of domestic applications, human behaviors and preferences for comfort vary according to cultural and individual factors. In this case, mathematical models could apply results from statistical surveys, but this would only represent a "standard" part of a population.

Unlike mathematical models, simulations provide a comprehensive approach to building design by using a range of building performance indicators to compare different design options at early design stages and to perform customized cost estimates before buildings construction stages. In the past few years, a wide variety of simulation programs are made available to represent the status and operation of a building, such as ESP-r, TRNSYS, DOE2, BLAST, EnergyPlus, IDA, etc. For example, EnergyPlus is a whole building energy simulation program that engineers, architects, and researchers mostly use to model energy and water consumption in buildings. Modeling the performance of a building with EnergyPlus enables building professionals to optimize the building design to use less energy and water. ESP-r is another integrated energy modelling tool for simulating thermal, visual and acoustic performance of buildings and the energy use and CO_2 emissions associated with control systems. The Modelica Buildings library is a free open-source library with dynamic simulation models for building energy and control systems. The library contains models for air-based HVAC systems, chilled water plants, water-based heating systems, heat transfer among rooms and the outside and multizone airflow, including natural ventilation.

These tools become a standard for computational science and engineering for innovative building energy management and control systems. However, efforts have been done focused mainly on simulating the performance of new systems such as hybrid HVAC architectures but not on the integration with hardware/software, controllers to reduce the energy consumption based on intelligent occupancy and real-time occupant requests. Furthermore, recent studies in this domain have shown that simulations cannot perfectly replicate the real dynamics that govern the energy use if not was coupled with occupant behavior simulations tools. Moreover, building energy simulation software's e.g. EnergyPlus and ESP-r, can combine the occupant behavior models with real simulation of energy such as ESP-r that offer an integrated behavioral models. Examples are the Hunt model for the switching of office lighting and the Lightswitch (Reinhart 2004) algorithm that model the interaction of occupants with blinds and lighting systems.

These tools could not be used to investigate the building as a complex system by considering, in a holistic framework, its physical properties (e.g., geography, building type, wind), its equipment (e.g., HVAC system, lighting, power appliances), outdoor environment (i.e., weather condition), occupants behavior and activities (e.g., reading, eating, walking), and auxiliary production of electricity or hot water (e.g., solar panel, hydrogen storage). Recently, a modular software middleware, called BCVTB, to interface between heterogeneous simulators was developed for easy integration and testing data exchanges prior the deployment in a building. In other words, the BCVTB is a software framework that allows coupling different simulation programs for co-simulation, and to couple simulation programs with actual hardware. BCVTB is based on the Ptolemy II software environment and allows, for example, simulating the building envelope in EnergyPlus and the HVAC control system in Modelica.

The aim of our work is to improve energy efficiency by using BCVTB for integrating EnergyPlus and the HVAC control system together with an occupant behavior simulator. We first focused on ventilation system modeling and introduced an intelligent control approach that relies on a state feedback technique to regulate the indoor air quality with the aim was to maintain indoor CO_2 concentration with an optimal ventilation rate while reducing energy consumption (Lachhab et al. 2015). The ventilation system was analyzed, modeled, and simulated using BCVTB as shown in Fig. 5. The obtained results showed that the CO_2-based state feedback control leads to better comfort with improved energy efficiency as compared to the traditional On/Off and PI controls.

We are currently integrating an agent-based tool to be linked to BCVTB for simulating and analyzing occupant behavior and preferences and their influence on energy efficiency while considering occupants' comfort. We are also planning to integrate models about renewal energy sources, energy storage systems, electrical cars, and how they interact with other components such as embedded sensors and actuators in the BCVTB framework. This will allow testing control hardware and software modules as well as formally verifying the new control techniques prior the real implementation and deployment in a building, which is a necessary step for

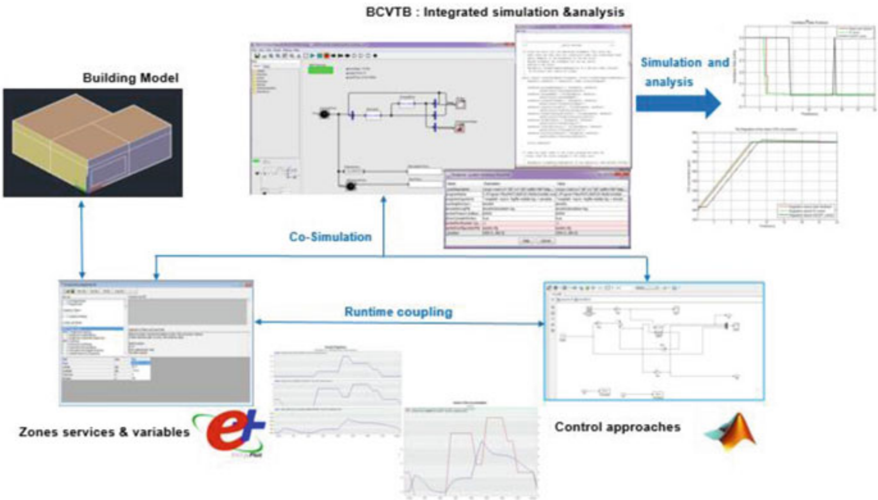

Fig. 5 The integrated simulation and analysis of the state feedback technique

developers and building design teams to design and construct more energy efficient buildings.

In parallel to this work aiming at first investigating new control mechanisms, we are developing a platform that combines intelligent complex event processing (CEP) (Lachhab et al. 2016a), predictive analytics, and event-triggered control techniques in energy efficiency buildings (Lachhab et al. 2016b). The architecture of the context-aware platform for complex and stream event processing (CAPS) is depicted in Fig. 6.

The platform architecture includes a wireless sensors network infrastructure (e.g., sensors, actuators, and smart meters), a building management and control system, a building occupancy tool, a CEP and stream processing engine, and a data collection tool. For example, different events will be received by sensors such as occupant number, CO_2 outdoor concentration, as well as the current ventilation rate. These events are continuously arriving to the platform and will be handled and processed by the in-memory CEP engine to provide situation-aware ventilation control of buildings according to the indoor CO_2 concentration of occupants. It is worth noting that complex event processing techniques are mostly used for detecting known patterns/events in the data stream. It is now possible to extract situational changes that are required to develop context-aware control techniques. These applications could react to the environment changes and occupants' behavior and preferences with the main aim is to make their life more comfortable according to their locations, current time, activities, and situations. While data extraction and real-time processing of relevant information are still a challenging task, it is now possible to adapt complex-event processing techniques (Lachhab et al. 2016a) and use predictive analytics for analyzing streaming data in real-time in order to generate

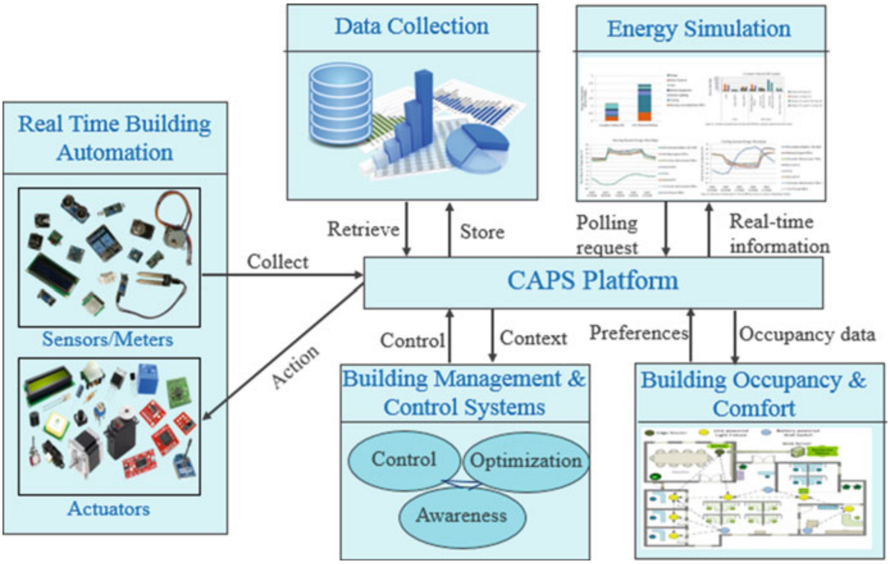

Fig. 6 The CAPS platform architecture

fast insights and then take suitable actions that are more suitable for detected changes and then prevent undesirable conditions from happening. For example, the increase in the concentration of CO_2 could be predicted and the ventilation could be adjusted (e.g. full-speed) before the concentration hits a critical level. It is also possible for predicting outside temperatures to provide intelligent heating control.

5 Conclusions and Future Work

Recent initiative for constructing energy-efficient buildings aims to deliver, implement and optimise building concepts that have potential to drastically reduce energy consumption and CO_2 emissions. It will increase the market for energy-efficient, clean and affordable buildings. Challenges are mainly to build building management systems for energy saving and CO_2 reduction, i.e., the development, the integration, and the real testing of several and different technologies and concepts such as energy sources and storage systems, HVAC networks, lighting system, electronic sensors and actuators, wireless communication technologies, artificial intelligence mechanisms, adaptive and learning algorithms, and data acquisition and mining.

In this chapter, we first surveyed exiting work from literature that is related to control approaches and solutions for energy efficiency in complex real buildings. Most important metrics are then presented by putting more emphasize on efficiency and comfort metrics and their relationships with building physical properties, equipment control, outdoor environment, and occupant behavior. Another section is dedicated to modeling and simulation tools of energy efficient buildings. We then introduced the necessity of an integrated and holistic tool (e.g., BCVTB) that could combine different simulation tools for real co-simulation of all sub-systems of buildings. To show the usefulness of BCVTB, we introduced a CO_2-based state feedback control scenario for ventilation system modeling and control. We showed also the necessity of intelligent building systems management that include run-time processing techniques of large amount of data in order to extract and detect undesired behavior or a specific pattern and trigger the suitable control technique (i.e., event-triggered control).

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Part III
Real-Life Examples

Modelling Space-Time-Action Modularity and Evolution of Living Systems

Pierre Bricage

Abstract We proposed a set of principles (Tables 1, 2, 3) based on the observation that all life forms are sustained by hierarchical juxtaposed and embedded networks (Fig. 1): *ecoexotope and endophysiotope*, with invariant properties: *gauge invariance of Life* (Fig. 2). Life is the most complex physical based phenomenon in the Universe, with a diversity of forms and functions over 62 orders of magnitude, from the Planck quantum level up to the whole Universe, and more . . . , that obeys *the ARMSADA paradigm* (La Violence. Colloque AFSCET, Andé, 7 p., 2000b; Vers une nouvelle systémique, Colloque AFSCET, Andé, 34 pp., 2010b). Many of the most fundamental phenomena scale with size according to power-laws (Paper presented at the international Colloque 150 ans après Darwin, 70 ans après Teilhard: Lire l'évolution, Paris, 109 pp., 2009a). In a surprisingly simple fashion, times (measured by the adult age of first reproduction: the time of generation *tg*) and sizes (measured by the volume at the growth phase ending: the adult 3D dimension *VA*) scale with *a power-law of exponent 3/2* (Fig. 7). The universality and simplicity of this fractal relation (Fig. 8) suggests that a fundamental universal principle of exchange of matter and energy, the Brownian motion (Fig. 9), underlies the organization of all living systems (Fig. 6): the Life's periodic Table of organization (Thermodynamique du changement, Colloque AFSCET, Andé, 63 pp., 2013a, Keynote World Conference on Complex Systems, Agadir, Morocco, 16 pp., 2014e, Revista Internacional de Sistemas 19:05–33, 2014f)!

1 Introduction

A lot of traits of species measured at different levels of living systems organization often appeared to ***scale as a power-law*** of organism body mass (M) and with exponents that are multiples of **1/4** (Duncan et al. 2007). From the ***molecular level*** $(i-3)$, to the ***meta-cellular organism level*** $(i+1)$, in animals, ***the slope***

P. Bricage (✉)
AFSCET The French Association for Systems and Cybernetic Sciences, Paris, France

IASCYS The International Academy for Systems and Cybernetic Sciences, Vienna, Austria
e-mail: pierre.bricage@univ-pau.fr

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of the log–log graph relationship between the mass (***x***, in g) and the metabolic power (***y***, in watts) was supposed to be **3/4**: Kleiber's law (Kleiber 1932). Thus metabolic rate was assumed to scale with body mass to the 3/4-power and the relationship had been united in *a **"metabolic theory of ecology"*** (Duncan et al. 2007). But significant deviations have been observed for different animals and plants taxa and different ecophysiological states (Glazier 2008). The connectivity networks for substrates in *Archaeoglobus fulgidus* or *Escherichia coli* (an archae and a bacterium, ***monera level*** $\boldsymbol{i-1}$) and in *Caenorhabditis elegans* (a multi-cellular organism, level $i+1$), shown ***on a log–log plot***, obtained by counting the incoming and outgoing links for each substrate and the number of reactions in which a substrate participates as a product, obey ***a scale-free network that fits a power-law*** (Jeong et al. 2000). A strong phylogenetic signal (Bricage 2010b) is given by the age of the organism at first reproduction but it does not scale to mass-corrected basal metabolism rate. The scaling between maximum population growth rate and organism body mass does not match with metabolic rate. The ***"metabolic-level boundaries" hypothesis***, one of the attempts to explain this, predicts that the ***power-law (log–log slope)*** of metabolic scaling relationships should vary between **2/3** (the optimal ratio square/volume for exchange at the surface of a sphere) and **1** (a slope of 1 indicating ***a linear relationship***), in "a systemic way" with metabolic level. Why such a discrepancy? How to define a standard scaling of the limits of a living system and which markers of functioning to use independently of the level of organization? Whatever the level, a system is always made of three kinds of entities: the Whole, its actors, their network of interactions (Figs. 1 and 4a). The system's characteristics, limits, and dynamics (Bricage 2014a, e) must be defined independently of its organization level, and conversely a level of organization (Bricage 2001b, 2009b) must be defined independently of what a system is (Fig. 6).

2 Actors: Dynamics Characteristics and Characteristics Dynamics

Ecosystems have a limited buffering capacity against biodiversity loss depending on their multifunctional redundancy (Takeshi et al. 2015). **Redundancy** is not about species but about the diversity of endophysiotopes integration (Fig. 1a) through the **diversity of interactions** (Fig. 2b1).

How can interactions between various levels of organization (Bricage 2009b), within and between systems, and within a same level of organization, be considered? How to highlight and model the fact that "***the Whole is both more and less than the sum of its parts***" (Bricage 2001a, b)? What about the "necessary and sufficient" measure and construction tools or principles? How to run to simplexity from complexity (Berthoz 2009; Bricage 2010a)?

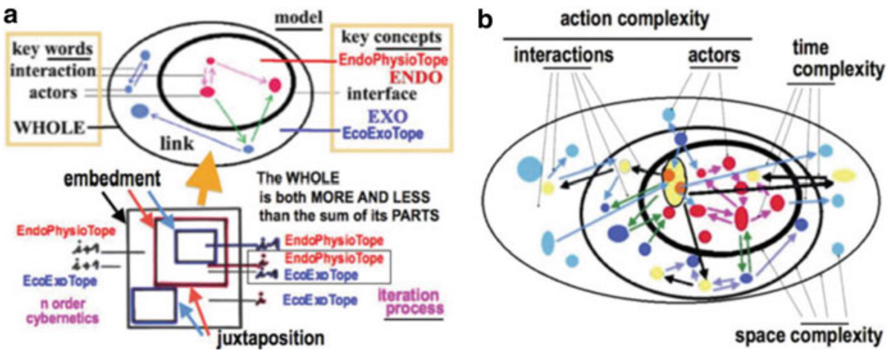

Fig. 1 In space, time and interactions, a system is both more and less than the sum of its parts. (Reproduced from Bricage 2000c, 2001b, 2002b, 2010a, 2011, 2013b, 2014d, e [Free Share-Alike Creative Commons Licence]) (**a**) Complexity: definition, measurement. The system's complexity is qualitatively and quantitatively defined by deconstructing it to characterize all its parts (reductionism). After reconstructing the Whole from the parts (holism), we can define complexity -because *we cannot explain new properties (**emergence**) by ancient previous ones*- with three parameters (for an applied software tool): –***actors complexity***: *the numbers of each kind of actor* (a different coloured point for each kind, all numbers give the total actors number, an actor is defined quantitatively by its surface), –***interactions complexity***: *the numbers of each kind of interaction* (a *coloured arrow* for each, each defined quantitatively by its thickness, all numbers give the total interactions number), –***time complexity*** given by the duration of all interactions taking place during a development phase (e.g. a time cycle of a step of survival) (Fig. 4b). (**b**) Limits: ecoexotope and endophysiotope. A system is made of three kinds of entities, **the actors** (*coloured points*), **their interactions** (*coloured arrows*) and **their Whole** (the system). A system is always a system-of-systems: the endophysiotope. **ENDO** of a $\boldsymbol{i}$ level of organization is the ecoexotope. **EXO** of survival of previous $\boldsymbol{i-n}$ levels. Due to the actors semi-autonomy, abilities of previous levels are lost, new ones are gained (Bricage 2000a). –***spatial complexity*** is given by the absolute and relative spatiotemporal limits (interfaces) of the embedded and juxtaposed food chains of the inter-active, interdependent **ecoexotope** (***exo*** external, ***tope*** space-time, ***eco*** of inhabitation) and **endo-physiotope** (***endo*** internal,***tope*** space-time, ***physio*** of functioning)

2.1 A System Must Be Defined Independently of Its Level of Organization: Functional Modularity and Modules Functioning, Systems Gauge Invariance

What are *the essential* "*minimum representations*" (Bricage 2006) to describe the invariance, the consistencies or unevenness of the living world (Bricage 1991), both in regarding its space (Bricage 2001b) and its time arrangements (Bricage 2005d, 2009b, 2013b), as well as its functional processes (Bricage 2000b, 2002b) and evolution (Bricage 2005a, b, c), at the local and global scales? (Figs. 1, 2, and 3).

The capability of moving matter and energy flows is the first requirement, before the capability of mass growth that it eventually allows, or not, depending on interactions between the EXO "hosting capacity" (**HOSTING**) and the ENDO

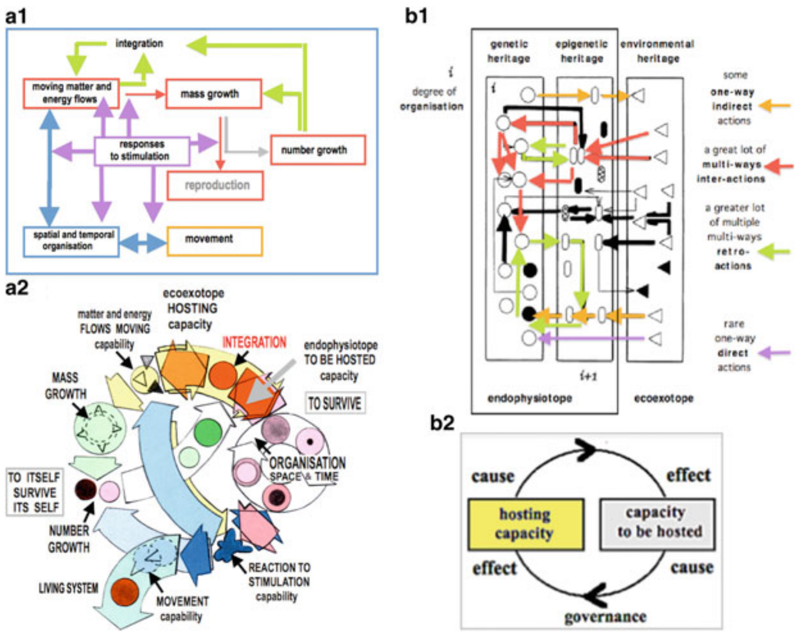

Fig. 2 A functional modularity defines each level of organization (Bricage 2002a, b, 2014d). (**a***1*) *The gauge invariance of living systems:seven mutually necessary and sufficient capabilities.* Each capability interacts with all others and itself. All capabilities mutually-reciprocally modulate their expressions (*coloured arrows* indicate interactions). (**a***2*) *The gauge invariance of living systems* (*coloured arrows* indicate capability steps changes). Soon or late, each capability is necessary to allow the survival of the system. A mass growing phase is always a prerequisite for a number growing phase. Interactions between **ENDO** and **EXO** are governed by HOSTING and HOSTED limitations. The time duration of the growth phase (Figs. 7 and 9) depends on the capability of moving matter and energy flows, which is controlled by the other capabilities inter-actions limits. (**b***1*) *Endophysiotope-ecoexotope interaction, the multiple heritages multiple roles: pleiotropy*. – ***regulation states***: in black '**off**' (inactivated, repressed, absent), white '**on**' (activated, induced expressed), or hatched '**unstable, unsteady**'. *–Interactions network*: *thin arrows* 'basic network' *thick arrows* '**specific differentiated network**'. *–**Regulation pathways***: *coloured arrows*. Each capability is a complex function of all heritages (as parameters for an applied software tool). The epigenetic heritage is acting like a buffer of interactions between ENDO and EXO. (**b***2*) *Systemic constructal law: into a net-work of actions, each actor is a cause of effects that are causes for feed-back effects.* ENDO activities continuously modifies the EXO hosting capacity (**HOSTING**) that in return modify the capacity to be hosted of the ENDO (**HOSTED**) and selects the interaction process (Fig. 4a). (Reproduced and adapted from Bricage 1991, 1998, 2000a, 2002a, b, 2003a [Free Share-Alike Creative Commons Licence])

"capacity to be hosted" (**HOSTED**). Matter and energy flows and mass growth are controlled by the capability to respond to stimulation. All are allowed because the ENDO and EXO parts of the system build a correlated structural and functional interactive organization, into space and through time (Fig. 1). The EXO and ENDO parts are linked forever in a Whole that cannot be partitioned, that is complete in

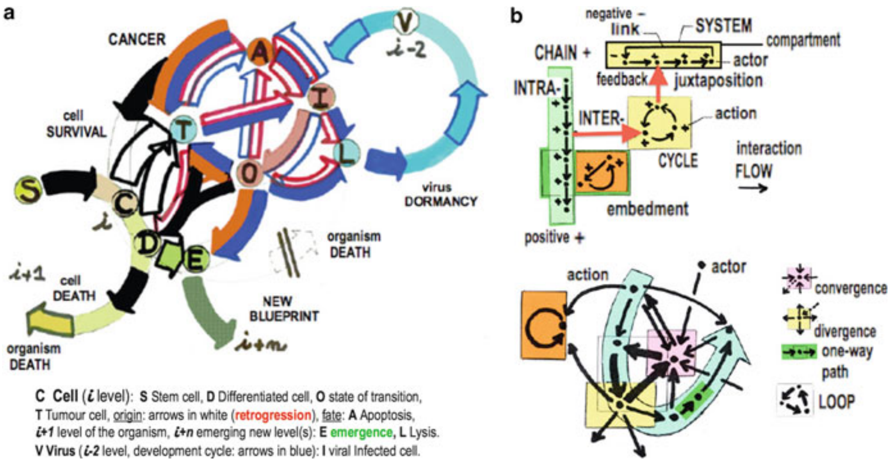

Fig. 3 A functional modularity defines all steps into a level of organization (Bricage 2002b). (Reproduced from Bricage 2002b, 2003a, 2005c, 2006 [Free Share-Alike Creative Commons Licence]) (**a**) Life cycle steps modularity. Example of a cell (***i*** level): **S, C, D** from birth to death, (organism level: $\boldsymbol{i+1}$), but true whatever the level of organization of a living system-of-systems (Fig. 6). (**b**) The space-time-action modularity. Example of metabolites flows ($\boldsymbol{i-2}$ level) (Fig. 6), but true whatever the network (Fig. 4a) of the level of organization of a living system-of-systems (Figs. 1 and 2b1) (Reproduced from Bricage 2002b, 2003a, 2005c, 2006 [Free Share-Alike Creative Commons Licence])

itself: this is the capability of integration. But each capability changes continuously because it is both the cause and the effect of the change of the another ones (Fig. 2b1). Continuously HOSTED is retroacting on HOSTING and reciprocally (systemic constructal law: Fig. 2b2). During its life cycle (Fig. 2a2), a living system, soon or late, expresses a capability of movement. At least one time during its life cycle (Fig. 3a), into at least one food chain, all capabilities (Fig. 2a1) are mutually necessary and sufficient for the survival of the system-of-systems, and this survival has only one goal, the reproduction of the life form: the capability to itself reproduce its self, for to have a offspring. These capabilities are seven qualitative “degrees of freedom” for to define a level of organization (Fig. 6).

2.2 A Level of Organization Must Be Defined Independently of What a System Is: Topological Modularity and Modules Topology, Endophysiotope and Ecoexotope Iterative Topology Through Embedding and Juxtapositions, Limits and Limitations

A system is always a system of systems: the endophysiotope of a level of organization is always an ecoexotope of survival for endophysiotopes of other organization levels (Figs. 1a and 3a). The ENDO activity continuously modifies the hosting capacity of the EXO (**HOSTING**) that in return (systemic constructal law) modifies the capacity to be hosted of the ENDO (**HOSTED**) (Fig. 2b2).

The interactions are limited by the HOSTING of the ecoexotope and the HOSTED of the endophysiotope. The semi-autonomy of embedded and juxtaposed spaces, "a space for each actor and each one in its own space", allows a better autonomy of the Whole. The independence towards the EXO, of a i level ENDO, is enhanced as the ENDO contains more juxtaposed and encased subsystems, of $i - j$ levels (Fig. 1a). Any level of organization is defined, as a Russian doll, by the number of encased fitted levels which it contains and by the number of levels in which it is contained and fitted (Fig. 6) (Bricage 2001a, 2005a, 2009b).[1]

2.3 As Spaces Are Limited Times Are Limited too and Conversely: Temporal Modularity and Modules Temporality, Clocks and Calendars

The semi-autonomy of embedded and juxtaposed times, "***one clock or one calendar for each actor and each one with its clock and in its calendar***", allows a better autonomy of the Whole. The system-of-systems is simultaneously temporal (Figs. 3b, 4b, and 5) (Bricage 2013b) and timeless (Bricage 2015).

The clocks of the living systems result from both external and internal time informations (Figs. 4b and 5a). The time modularity (Figs. 3a, 4b, and 5b) is revealed by the existence of rhythms at different scales (Bricage 2005d, 2010b, 2013b). These rhythms are unique by their latency, their periodicity, their lag time -of organization- and their time shift of regulation (Bricage 2005d). All modelling has to take into account simultaneously the concepts of—temporal window: "Before the time, this is not the time. After the time, this no longer is the time.",—time latency and time shifting: "It is necessary to give some time to the time."—compartmentation of the time: "There is a time for each event. And each event is located into its time place.", and—the non-linearity and non-summation of time: "The temporal Whole is both more and less than the sum of its parts." (Figs. 2a2, b1, and 5). The arrow of the time structures the clocks of the living systems. But, -systemic constructal law- (Figs. 2 and 7), the living systems structure back the arrow of their time(s) (Bricage 2013b).

[1]key notions: ***ergodicity*** (http://www.afscet.asso.fr/ergodiqW.pdf Accessed 2 Dec 2001), ***interactive-spacetime field*** (http://www.afscet.asso.fr/resSystemica/Paris05/bricage3.pdf Accessed 31 Sept 2005), *scaling* (http://www.armsada.eu/pb/bernardins/phylotagmotaphologie.pdf Accessed 19 Nov 2009)

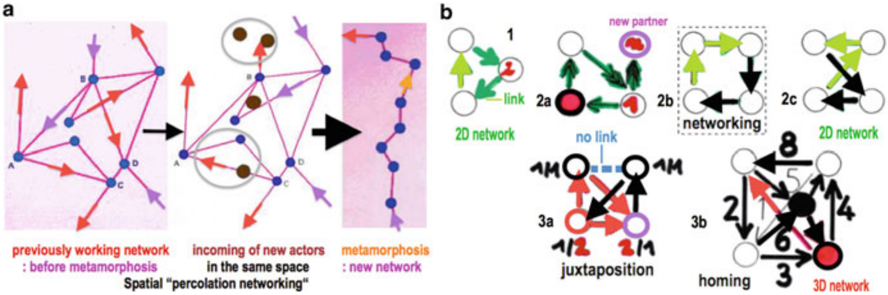

Fig. 4 A percolation process leads to emergences of new systems of cooperating interactions. Whatever the organization level, the encasement and juxtaposition of the parts (Fig. 1), obeys the same process: ***a spatial-temporal and structural-functional metamorphosis*** (2005a, b, c). (**a**) *Emergence: a network metamorphosis process*. **b** *A one way cycling functional calendar.* Within a periodic time cycle (**b**) of the functioning network (Figs. 3b, (**a**)) of an Association for the Reciprocal and Mutual Sharing of Advantages and DisAdvantages (**ARMSADA**) (Tables 1 and 3), there are always three simultaneous processes for the **metamorphosis** that allows to enter the cooperative process for to merge into a new Whole, for homing new partners, through changing the spatial (**a**) and temporal (**b**) dimensions of the previous system: –lysis of ancient structures with the disappearance of previous actors during the interactive process of integration of at least one new actor, –creation of new functional structures, new actors that were not there before, are integrated *into* '*the coming network*', –ancient actors are conserved but '*transformed*' in their action, or in their place, or in their time of action (Bricage 2008). Integration is depending both on ages and stages of the actors, their interactions and the Whole (Figs. 1a, b, and 2b1). Connections for a new network (Figs. 1b and 3b) often show a threshold behaviour. When there are few connections, there are isolated islands of connections, and the largest connected group is a small fraction of total members in the network. However, at some point, the addition of just a few more connections can cause a substantial fraction of the network to be connected (**a**). A rhythm emerges (**b**) with **a one way cycling network** (both an Eulerian and Hamiltonian cycle), only when the partners are sharing advantages and disadvantages, not only for the space limitations (constraining closure), but also for the functional time flow (Figs. 3b and 5a), **one after one at a time, not only in a spatial autonomy but also in a temporal one:*"A space for each one and each one in its space" and "A time for each one and each one in its time"***. When a new partner (**b** *-2a-*) enters the association, the same equal repartition of time use (**b** *-1-*) must be restored, with one choice of two possibilities (**b**, *-2b-*, *-2c-*) in a '2D network'. When another actor enters the time pathway there is only one way of cycling for an equal time sharing (**b** *-3b-*) into a 3D network, ***a new dimension is emerging from the merging closure constraints***. New structures and properties appear, ancient ones disappear, ancient ones remain but changed. The system complexity (Fig. 1b) results from a punctuate equilibrium process of successive metamorphoses (Bricage 2001b, 2005a, b, c, d) that simultaneously structures spaces (**a**) and times (Figs. (**b**) and 5a) (Bricage 2013b). The stability and resiliency of a system, while facing to changes of its endophysiotope and ecoexotope, is depending on the number of actors and the percolation process of their interactions. Emergence (Fig. 6) is always a spatial and temporal, structural and functional, metamorphosis within a periodic cycling (Fig. 5) equal sharing network (**b**). (Reproduced from Bricage 2005c [Free Share-Alike Creative Commons Licence])

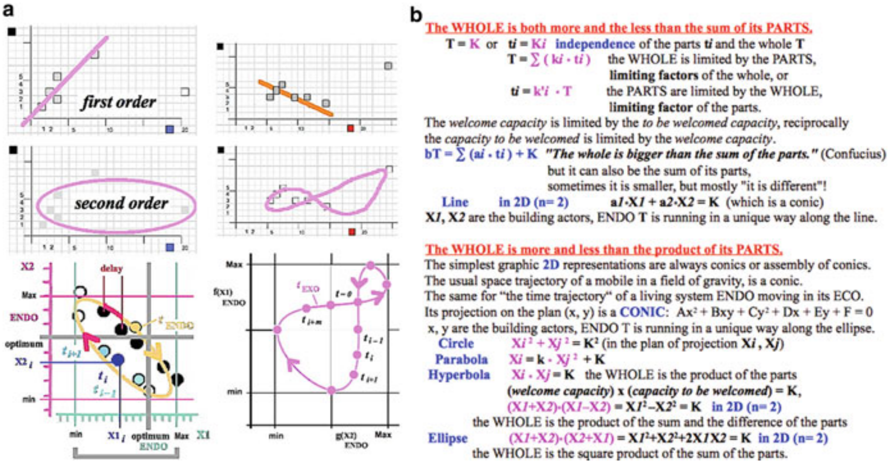

Fig. 5 Time modules are "one way cycling" functional calendars of cooperative interactions. (**a**) *From first order to second order cybernetics. Top*. -first order relationship- *line* (linear adjustment): –agonism, amplification (*left*: FSH-LH, menstrual cycle), –antagonism, negative feedback (*right*: FSH and oestrogen, menstrual cycle). *Middle and down*. -second order timelines- *ellipse* (*left*): ENDO timeline built by two antagonist actors analemme (*right*): two agonist actors EXO timeline control -glycaemia- (*left*), -man sleep- (*right*). (**b**) *Time building by juxtaposed embedments*. Time calendars are running along conics. Like spaces, times are more and less than a sum of their parts, like structures and functions are. All capabilities of the gauge invariance state are usually non-linear (Bricage 2013b). Timelines are designed as ellipses projected on a plan or a Moebius strip and labelled alongside with dates and events on points where they absolutely have to happen (**a**). The emergence of a new blue-print (Figs. 4, 6, Table 1) runs through the juxtaposition and embedment of previous systems (Fig. 1). The new time of the Whole emerges through the simultaneous metamorphoses of the parts into their Whole (Fig. 4a). Each subsystem maintains its space–time identity into the Whole with which it is a partner, a Parcener. The partial autonomy of each partner is allowed through the maintenance of individual or collective spatial and temporal boundaries (Bricage 2005a). (Reproduced from Bricage 2010b, 2013a, b, 2014a [Free Share-Alike Creative Commons Licence])

3 Interactions: Ontogeny of Interactions and Interactive-Space-Time Ontogeny

Whatever its level of organization, a new system will always emerged through a three processes metamorphosis way (**exaptation**):—new properties and structures which did not exist before appear (percolation emergence through space and time),—ancient properties and structures of the previous levels are definitely lost,—some ancient properties and structures are remanned (Fig. 4).

Table 1 Making an **ARMSADA**: advantages/disadvantages for the parts/the Whole. (Reproduced and adapted from Bricage (2001a, 2003b) [Free Share-Alike Creative Commons Licence])

There is NO advantages WITHOUT dis-advantages.

First advantage :
For THE BEST: emerging of a new capacity of being hosted within ecoexotopes where there was for the endophysiotope, until then, no capacity of hosting.
Second advantage :
To a TALLER WHOLE: a jump in spatial scaling.
To a MORE DURABLE WHOLE: a jump in time scaling.
First disadvantage :
For the WORST: if one of the "parceners" dies, the other one does so too.
Second disadvantage :
LOSS of previous properties: The new Whole is LESS than the sum of its parts.

The setting up of an ARMSADA allows "to survive" and "to re-produce its self" through the creation of a new system with an upper level of organisation.
BUT ONLY IF
First requirement :
Each one's growth is limited by that of each others.
Second requirement :
For ONE to survive, the OTHER ONE must survive first.
The mutual survival is depending on reciprocally shared restrictions.
All the partners MUST simultaneously lose the capacity of killing each other ones.

3.1 To Share Advantages and Disadvantages: ARMSADA, the Only Way for a Viable Spatial, Temporal and Functional Integration

Whatever the level of organization there are never advantages without disadvantages. All that is an advantage for a level may be a disadvantage for previous or a next one (Bricage 1998, 2010b, 2011, 2014b, g). "***To survive that is to turn disadvantages into advantages and to avoid advantages turning to disadvantages***" (Bricage 2000a, b, c). The only way to survive to emerging and past disadvantages is to share all disadvantages and advantages into an **A**ssociation for the **R**eciprocal and **M**utual **S**haring of **A**dvantages and **D**is**A**dvantages (**ARMSADA**) (Bricage 2000b, 2001a, 2005b, 2007, 2008, 2009a, 2010a, 2011, 2014b, c). In such an association, all that is an advantage for a partner is a disadvantage for at least another one, and reciprocally (Table 1) (Bricage 1998). And the embedded levels of organization are always antagonist for their local survivals but agonist for the global survival of their Whole (Fig. 6) (Bricage 2007, 2008, 2014c).

The lichens are associations between an alga and a fungus. The organization level of the lichen is higher than the organization levels of each of the partners. The lichens elaborate molecules that no other fungus or alga can elaborate. They are ecosystems that contain a food chain. The survival of the lichen's organism is based on **a steady state of sharing of advantages and disadvantages between the two partners** (Bricage 1998): the benefits for a partner are injuries for the other one and reciprocally. In order to survive, the fungal partner has to limit its aggression

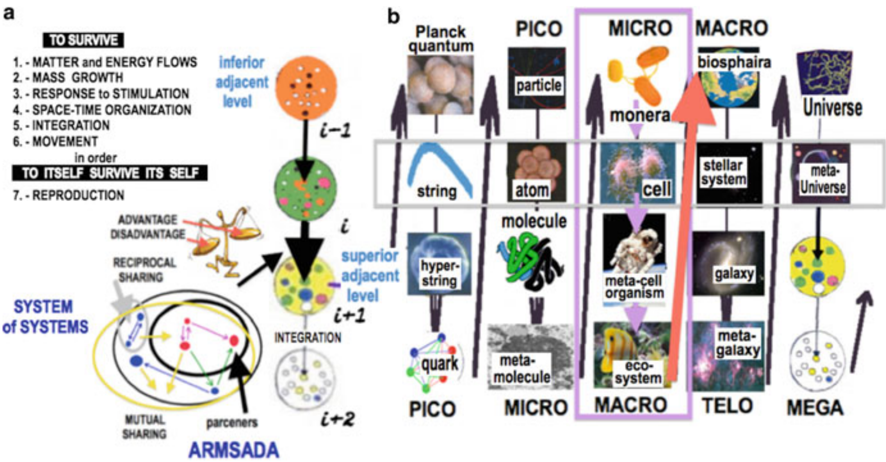

Fig. 6 The spatial fractal structures of embedments and juxtapositions of living systems. *"What does he know about deserts the one who is looking only at a grain of sand? What will he know of a grain of sand the one who sees only the desert?"* (**a**) The two constitutive paradigms the gauge invariance seven capabilities (Fig. 2a1) and ARMSADA emerging jumps (Table 1). (**b**) The periodic table of living systems classification. Each *column* is a series of systems of the same limiting interface between EXO and ENDO (Fig. 1). Each *line* is occupied by systems that are at the same evolution step. The end of each *column* corresponds to the emergence of a new limiting interface (so we can equally put the end of a column at the beginning of the next one or not). For example, monera (MICRO-scopic level, $\boldsymbol{i-1}$), at the beginning of a series, are limited by a membrane (*"a wall"*) which is a multi-meta-molecular aggregate that emerged from the adjacent inferior step ($\boldsymbol{i-2}$) -at the end of the previous column-. Cells (unicellular organisms, arbitrary refereed as $\boldsymbol{i}$ level) are also limited by a membrane, and the cellular organelles, endosymbiotic monera-like compartments (Bricage 2001b, 2005a, b, c, 2009a), are limited by a membrane too. Meta-cellular organisms ($\boldsymbol{i+1}$) are also limited by a barrier, which results from the accumulation of membranes of specialized protective cells, that built a new wall made of juxtaposed and embedded membranes (a new interface between a new ENDO and a new EXO, a new blue-print). With ecosystems ($\boldsymbol{i+2}$ level) of organisms from the previous levels (a cell, $\boldsymbol{i}$, which is an ecosystem of bacteria, $\boldsymbol{i-1}$; a multi-cell organism, $\boldsymbol{i+1}$, which is an ecosystem of cells, $\boldsymbol{i}$) a new limiting **interface** emerges which is a new mode of **limitation**, *"an ecosphere"*, for the next column. From Planck quantum to quark(s) (PICO-scopic levels column) the interactive space-time field is structured by strong intra-nuclear forces (*physical behaviour*), from particle(s) to meta-molecule(s) levels (from PICO- to MICRO-scopic levels) the interactive space-time field is structured by weak inter-atomic forces (*chemical behaviour*) (Klein 2014), from monera to ecosystem(s) levels (from MICRO- to MACRO-scopic levels) the interactive space-time field is structured by weak electromagnetic inter-molecular forces (*biological behaviour*), from biosphere(s) to ecosystem(s) of galaxies levels (from MACRO- to TELO-scopic levels) the interactive space-time field is structured by gravitational forces (*mass behaviour*) (Englert 2014). Whatever the level, mass is creating space (and time) and reciprocally space is creating mass (Fig. 7). (Reproduced and adapted from Bricage (2001b, 2009a) [Free Share-Alike Creative Commons Licence])

on the alga associate. As lodging host, the fungus pays a double cost:—the cost of the accommodation of the alga,—the cost of a growth limited by the growth of the alga. In order that the fungus survives it is **necessary** that the alga survives **first**. To survive, the alga partner, the lodged host, also pays a double cost:—the cost of the surviving of its population of cells, through the non-survival of a part of it, which is eaten,—the cost of a growth limited by the growth of the fungus (Table 1).

The growth of each partner is **limited** by the growth of the other (Bricage 1998, 2006). One may survive only if **the other one must survive first**. The fungus has to limit its growth demands with respect to the alga. Reciprocally the hosted alga may develop itself only **into the limit of the carrying capacity** of the hosting fungus. **The mutual survival is depending on reciprocal limitations**. But, the survival is possible and the acquisition of new capacities is allowed too, even in conditions of global growth close to zero. And, if the one dies, the other dies (Bricage 2000a, b). The two totally interdependent partners form just only **a Wholeness**. Together they survive in ecoexotopes where there is no sustainability for each partner separately. **The Lichens' symbiosis is a partnership of mutual sharing of profits and injuries**, but not a win-win association! It emerges because the two partners are not simply added but combined and interpenetrated in a new Whole **"an Association for the Reciprocal and Mutual Sharing of Advantages and DisAdvantages"** (Table 1). They metamorphose themselves simultaneously (Fig. 4a) in a new, unique, different, whole organism. The autonomy of the partners and their Whole is built on their interdependence (Bricage 2005a).

Cancer is the result of **the failure of the capacity to be hosted of the endophysiotope** of our cells, **in response to the failure of the hosting capacity of their ecoexotope of survival,** the organism (Bricage 2008). There is only one rule for the survival: **"to transform disadvantages into advantages" and "to prevent advantages turning to disadvantages"**. When the ecoexotope is changing, a disadvantage can turn to an advantage and conversely. For stressed endangered cells, cancer is the way not to die. **Cancer is a response for best survival of damaged cells!**

The genome of all organisms is inhabited by viruses. The presence of these constrained dangers is usually an advantage for the survival of both the inhabited cells and their inhabitant viruses: **the genetic material of a cancer virus is inserted into the host cell genome without any production of virus particles and with no cell death.** Cancer is a disease of dis-functioning cellular genes (Fig. 3a) due to unwanted viral gene expression (Bricage 2008).

The stability of a cancer cell is in the key fact that *the virus does not kill the cell* and *reciprocally the cell does protect the virus of its killing by other cells*. The result is the emerging of a new spatial and temporal network, a new mode of integration, into a transformed **Association for the Reciprocal and Mutual Sharing of Advantages and of DisAdvantages,** within the cell… an advantage for the "new" cell but a dis-advantage for the organism inside which the new "re-autonomy" of the cancer cells disrupts the previous steady-state's controls. Like that of a bacterium infected with a phage, the fate of a cancer cell is depending on the interactive percolation with its invading virus (Fig. 3a) (Bricage 2005b, c). Cancer is induced by agents of cellular provirus lysis! That explains the heterogeneity of the disease, its evolutions and the diversity of the potential hosts.

In order that one survives, it is necessary that the others survive first, and reciprocally

"The way is both the cause and the consequence of the history." (systemic constructal law)

Cancer is a disease of the breakage of the Association between the "parceners". Usually the breakage of the Association for the Reciprocal and Mutual Sharing of Advantages and Dis-Advantages (ARMSADA) leads to apoptosis (Bricage 2005c), but sometimes to cancer (Fig. 3a) (Bricage 2008).

3.2 The Periodic Table of Biological Systems Organization Levels

Balancing from individualism to the merging of individualities into collective neo-individualism, the process of ARMSADA rising has allowed the emergence of new life forms (Bricage 2010a). It is an "only one way" evolution in which "turning dis-advantages into advantages and avoiding advantages turning into dis-advantages" (Table 2) allows an exaptation process for **new ENDOs** that are more and more independent of their **previous EXOs** (Bricage 2006): it is the only way to escape from the dilemma of the predator-prey game where finally the predator always wins and thus loses (Bricage 2014a, b) (Tables 2 and 3).

Like lichens or legumes' nodes, only will survive the Associations for the Reciprocal and Mutual Sharing of Advantages and DisAdvantages. From the simplicity of the Monera to the complexity of the cell and the hyper-complexity of the lichen, the blue-prints of the building of new system-of-systems have preserved the ancient footprints of the previous life forms (Bricage 2005a, 2009a) (Fig. 6).

The gauge invariance of life (Fig. 2a1) explains the scaling invariance of processes like the growth: the mathematic law of growth (Fig. 7b) is independent of the organization levels (Bricage 2009a). With two new words -ecoexotope and endophysiotope-, with three basic concepts -to survive it is to eat and not to be eaten, soon or late it is impossible not-to-be-eaten and there are no advantages without disadvantages-, with one new qualitative paradigm -soon or late a new living system rises from the merging into an **ARMSADA**-, with two evident facts -the gauge invariance of the living systems (their seven mutually necessary and sufficient capabilities) and the modularity and ergodicity processes (every new living system is built through juxtapositions and encasements of previous ones)- (Table 3), it is possible not only to explain living evolutionary phenomena -like the origin of the cell (Bricage 2005a, b)- but also to foretell a methodology to obtain curative vaccines (Bricage 2005c, 2008)—that is effective in the case of HIV (Bricage 2005c, 2008, 2014b).

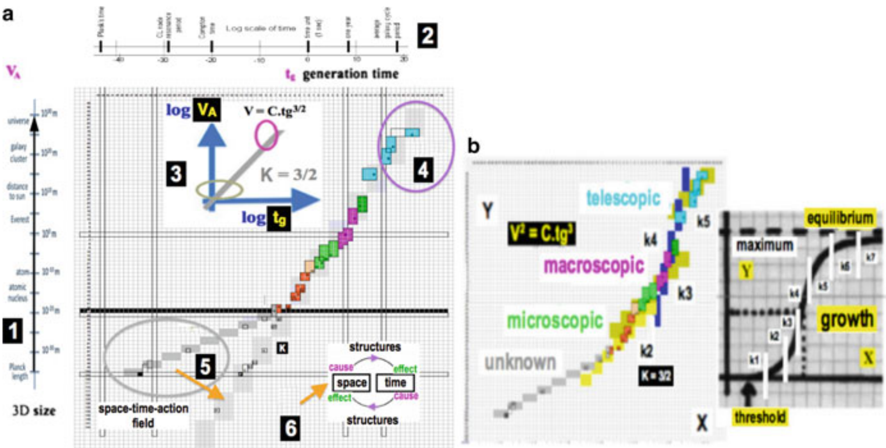

Fig. 7 The space-time fractal of embedded and juxtaposed structures functionalism: vidence for a developmental-growth allometry. (**a**) The whole Universe time-space relationship: **VA = Ctg3/2**. Living systems order of magnitude, for length (L = **1D**in meters) and time (**t**in seconds), in powers of 10 Lengths: visible diameter of ***the Universe*****10 + 26 m**, of ***the Earth*****10 + 7 m**, of ***a cell*****10 − 5 m**, of ***an atom*****10–10 m**, of its ***nucleus*****10–15 m**, of ***a particle*** like a proton or neutron **10–16 m** or an ***electron*****10–17 m**, of ***a quark*****10–18 m**, of **a string 10–34 m**, ***Planck length*****10–35 m**, ***initial size of the Universe*****: 10–35 m for 10–43 s**, ***space volume*****V = kL3**. Time or durations: ***age of the today Universe*****more than 10 + 18 s**, ***time of generation(tg) of a cell*****10 + 4 s**, ***lifespanof a boson*** or a free quark **10–24 s,*****Planck time*****10–43 s** (Bricage 2009a).

1 **Y** spatial organization level (**1D scale** in powers of **10**) volume **V** (**3D**) in **3Y** power: **adult volume VA** (of a sub-spherical system). **2** **X** temporal organization level (scale in powers of **10**): **time of generation tg**, duration for achievement of the juvenile growth phase, inferior of lifespan (Fig. 2a2). In the quantic world, from Planck to quarks scale (Fig. 6), if we exchange (mirror symmetry) time and space (grey cases, *orange arrow* **5**) we get a better linear adjustment (**3** *grey line* **K = 3/2** slope). Time is at the origin of space, reciprocally space is at the origin of time **6** (systemic constructal law). (**b**) The whole Universe logistic growth curve. The global whole Universe growth obeys a logistic curve, with a threshold (located under the *black horizontal line*, in the **5** part of (**a**) graph) and a plateau (mark of the end of the growth phase) which is not attained in the case of our Universe (part **4** of (**a**)). The local organization levels (the *columns* of Fig. 6) are associated to local growth rates (**k1**, **k2**, ...), the **K = 3/2** value corresponds to the slope at the inflexion point of that sigmoid curve. 3/2 = 2 × 3/4 [with 3/4 the power-law exponent of the metabolic theory of ecology (Duncan et al. 2007)]. (Reproduced from Bricage 2009a, b, 2003b, 2014f [Free Share-Alike Creative Commons Licence])

Table 2 The systemic laws of survival of all living systems: ***the ineluctable emergence of a system-of-systems as an ARMSADA, a "natural contract"*** (Adapted from Bricage 1976, 1982, 1984, 1986, 1988, 1991, 1998, 2000a, c, 2001a, 2002a, b, 2003b, 2006, 2011, 2014d; Bricage et al. 1990 [Free Share-Alike Creative Commons Licence])

The LAWS

Law 1a - for every living system, to survive that is first **"to eat" and "not to be eaten"**.
Law 1b - but it is "impossible not to be eaten", **unavoidably, soon or late, everyone is eaten !**
Law 2 - to survive ... but only in order **to survive its self** (to re-produce its life form): life does rebirth from life!
Law 3a - integration: every living system cannot be "extracted" from its ecoexotope of survival.
Law 3b - **gauge invariance**: in order to survive for to itself reproduce its self, every living system owns 7 functional characteristics (or **qualitative invariants**, or **capabilities**, or freedom degrees) which are mutually necessary and sufficient: 1. the capacity of **moving flows** of matter and energy, 2. the capacity of **growing in mass**, 3. the capacity of **reacting** to stimulations, 4. the capacity of **maintaining an organization**, that is built, controlled and regulated into space and through time (its endophysiotope space-time-action field), 5. the capacity of **integration** (into an ecoexotope), 6. the capacity of **movement**, and 7. the capacity of **reproduction** (with eventually a growth in number)

Their effective "adaptive" CONSEQUENCES

Consequence 1a: A genetic heritage (endoPHYSIOtope) allows "to eat". It can also allow "not to be eaten". It is transformed along the way life goes through. There are **different versions** (the genoType) of that heritage, and all **have both advantages and disadvantages**.
Consequence 1b: An environmental heritage (ECOexoTope) allows "to eat". But it cannot allow "not to be eaten". It is transformed along the way life goes through. There are **different versions** (the bioTope) of that heritage, and all **have both advantages and disadvantages**.
Consequence 1c: An epigenetic heritage (EcoPhysioTope) allows "to eat" and also can allow "not to be eaten". It is transformed along the way life goes through. There are **different versions** (the phenoType) of that heritage, and all **have both advantages and disadvantages**. That heritage is **continuously structured and modified** by flows of matter, energy and information. It is **both the cause and the consequence of the history** of each living system (**contingency**). It plays a role of **"violence buffering"** between the genetic and environmental heritages. In fine, it is **both the cause and the consequence of the integration** of the EndoPhysioTOPE in the EcoExoTOPE of survival. Thus it is also **both the cause and the consequence of the space-time-action field organization**.
Consequence 2a: The increase of the HOSTING capacity of an ECOexotope **for only 1** species leads to the increase of the violence between the other species that were previously involved in the same **network of sharing Advantages and DisAdvantages**.
Consequence 2b: Any shift in the balance between ADVANTAGES/DISADVANTAGES may result in an **unpredictable and irreversible change**.

The CONTRACTUAL FUNCTIONING of the living systems-of-systems

Act 1 : To survive that is
"to turn disadvantages into advantages" and "to avoid advantages turning to disadvantages"
Act 2 : Organization and integration run **through juxtapositions and encasements** of previous systems-of-systems
Act 3 : The merging into **Associations for Reciprocal and Mutual Sharing of Advantages and DisAdvantages** allows an emergence of a durable development, because it is **sustainable** for **and sustained** by all partners.

Using the gauge invariance paradigm for the definition of a level of organization (Fig. 2a1) and the ARMSADA paradigm for the obligate emergence of a new blue-print through a ARMSADA merging process (Tables 1 and 3) we can define the steps of living system-of-systems evolution and the jump process (Bricage 2002b) leading from a level (emerging from previous adjacent inferior levels juxtapositions and embedment) to another one (adjacent superior level) (Fig. 6a). The emergence of a new blue-print results from the transcendence and transgression of ancient systems. This runs always through the juxtapositions and embedments of a bit of previous systems (Fig. 1).

Table 3 ARMSADA a revisited paradigm of symbiosis (Reproduced from Bricage 1998, 2000b, 2003b, 2010a [Free Share-Alike Creative Commons Licence])

"A puzzler's attitude"...

2 NEW WORDS : 2 types of space-time-action fields ECOEXOTOPE and ENDOPHYSIOTOPE

3 TRIVIAL BASIC CONCEPTS :

- TO SURVIVE THAT IS TO EAT and NOT TO BE EATEN
- SOON OR LATE IT IS IMPOSSIBLE NOT TO BE EATEN
- THERE ARE NEVER ADVANTAGES WITHOUT DISADVANTAGES

1 NEW QUALITATIVE PARADIGM :

SOON OR LATE, ALL NEW LIVING SYSTEMS EMERGED FROM AN ARMSADA

ASSOCIATION for the RECIPROCAL and MUTUAL SHARING of ADVANTAGES and DISADVANTAGES

2 ANCIENT EVIDENT FACTS :

- GAUGE INVARIANCE

EVERY LIVING SYSTEM ALWAYS OWNS 7 CAPABILITIES :

- To Move MATTER and ENERGY FLOWS, - To React to STIMULATION, - To MAINTAIN into a space-time-action field, an ORGANIZATION, its ENDOPHYSIOTOPE, - To be INTEGRATED into an ECOEXOTOPE of survival, - to MOVE itself, in order to SURVIVE, - to GROW, - To survive but to REPRODUCE ITS SELF

- MODULARITY and ERGODICITY

EVERY NEW LIVING SYSTEM IS BUILT TRHOUGH JUXTAPOSITIONS AND ENCASEMENTS OF PRE-EXISTING ADJACENT SYSTEMS, both functionally OPENED and structurally CLOSED

2 NATURAL QUANTITATIVE PARAMETERS and 1 NEW QUANTITATIVE LAW :

- ADULT VOLUME, measure of the closure, the LIMITS of an ENDOPHYSIOTOPE into its ECOEXOTOPE
- TIME OF GENERATION, measure of the age of acquisition of the capability of REPRODUCTION
- a FRACTAL structural-functional EVOLUTION power-law $V_A = C.\ t_g^{3/2}$

The new Whole, in terms of mass and metabolism (Fig. 3b), space (Fig. 1a), time (Figs. 4b and 5b), actors (Fig. 4a) and interactions (Figs. 1b and 4b) is both more and less than the sum of its parts. It emerges through the simultaneous metamorphoses of the parts into the Whole (Fig. 4). But each host maintains its identity into the Wholeness of which it is a partner (Bricage 2005b). The partial autonomy of each partner is allowed through the maintenance of individual and collective boundaries (Bricage 2005a). These interfaces structure the spatial and temporal integration of the parts into the endophysiotope of their Whole, and of the Whole into the ecoexotope of its survival. The transition from one level of organization to an adjacent superior one (Fig. 6) is the result of the building of a new, spatial and temporal, network. In this new orderly spaced-timed system all braces are allowed and each partner owns a special place, both through the time and into the space (Fig. 4).

Whatever its mode, the integration of the parts, and simultaneously of the Whole, emerges only through the building of an ARMSADA (Bricage 2006) (Table 2).

In a no-change ecoexotope, this allows the maintenance of the diversity of the partners and the unity of the Whole. If the endophysiotopes or the ecoexotopes are changing, this is the only way to make a new networking mode of organization and integration. The associations emerge through the interactive fitness between the "to welcome" capacity of the ecoexotope and the "to be welcomed" capacity of the endophysiotope of each parcener. This is allowed only through the simultaneous losses by all partners of the capacity to kill the other ones (Table 1) (Bricage 2011).

"A pebble is not alive but there are living systems into a pebble." (Bricage 2009a). Because, through a change of space-time-action-energy scale, an atomic reaction can restore the ecoexotope conditions of energy allowing endophysiotopes of systems at the atomic level ($\boldsymbol{i-4}$) (Fig. 6) to fuse and fission. Within its space-time-interaction field (level $\boldsymbol{i-4}$) an atom is as alive as a molecule (adjacent superior level $\boldsymbol{i-3}$), a cell (level $\boldsymbol{i}$) or a galaxy (level $\boldsymbol{i+5}$) (Fig. 6b). All these levels own the seven capabilities (gauge invariance) (Fig. 2a) that make their endophysiotopes alive but only if the hosting capacity of the ecoexotope allows their active survival (Fig. 1).

ARMSADA emergences shape the evolution of species and ecosystems and the emergence of biological complexity (Figs. 8 and 9). Under specific conditions (Fig. 10), changes of the shared EXO induce free-living ENDOs to become obligate mutualists (Table 1) and establish a set of observably phylogenetically related systems (Fig. 6b).

3.3 Evidence for a Developmental-Growth Functional Allometry

No system can be defined as an independent closed space but as an independent, autonomous closed time (Bricage 2013b). Time modularity is evidenced by rhythms at different scales (Figs. 5a and 8). Endogenous rhythms are built as a result of past interactive responses (time delays, entrainments and breakages) between the endophysiotope of functioning (ENDO) and ecoexotope of survival (EXO) (Bricage 2005d). The temporal Whole is both more and less than the sum of its parts. The time arrow structures the space functionalities of living systems. But, the systems compartments structure back the arrow of their time (Fig. 7a). Time knowledge requires skills and tools to be designed by the system so as to manage time when accomplishing specific tasks to survive.

Metabolic activities of populations of a same food chain are often synchronized. The monera ($\boldsymbol{i-2}$ level) growth curve is a sigmoid or logistic one. The "duration of survival" and the "time of generation" (the minimal duration of the growth phase that is necessary and sufficient for a bacterium to divide, tg) obey a power-law. The maximal lifespan of mammals and birds is linked to Entropy according to a power-law of exponent $+1$, e.g. an hyperbola (Fig. 10), the same for the time of generation and Entropy, correlated with mass according to a $+\mathbf{1/3}$ exponent power-law.

The transition from one level of organization to a superior one results from the building of a new spatiotemporal network. In this new orderly spaced-timed system, many braces are allowed, but each partner owns a special place, both through the time and into the space. The Whole emerges with the building of an Association for the Reciprocal and Mutual Sharing of Advantages and DisAdvantages. That allows

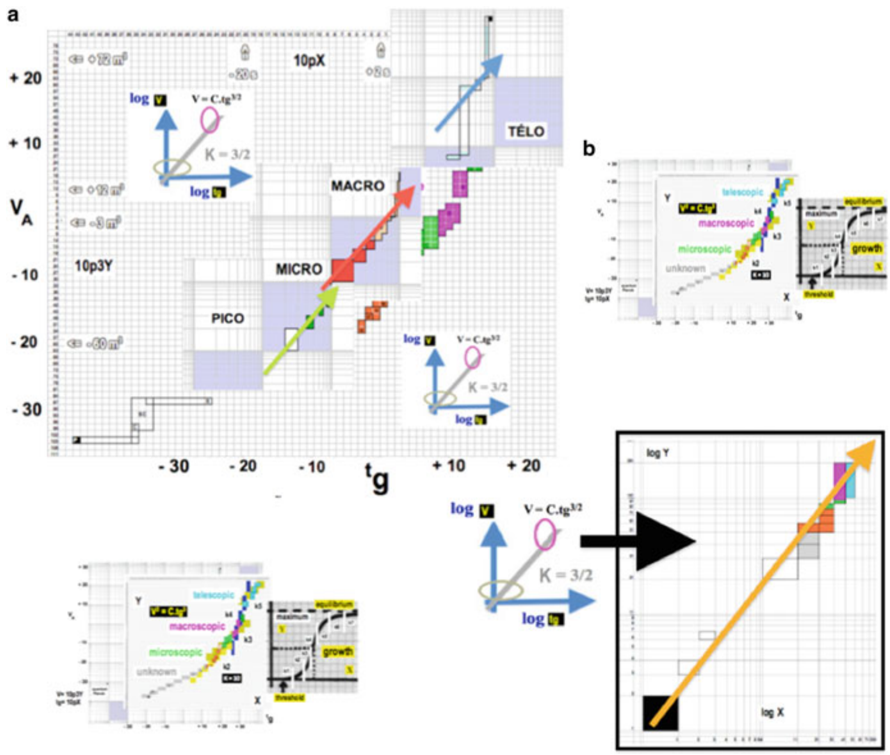

Fig. 8 (**a**) Up to bottom emergence and organization, (**b**) From bottom up emergence. During the life evolution process, new endophysiotopes of living systems-of-systems are emerging through an iteration process of embedment and juxtaposition (Fig. 1) of pre-existing systems. Each ENDO is a system-of-systems. An ENDO of a ***i*** level of organization is the EXO of survival of an ENDO of ***i − 1*** level and, mutually, a ***i − 1*** level EXO is integrated into a ***i*** level ENDO. That allows the emergence, with an effective great diversity, of new modular blue-prints (Fig. 6). **VA2 = C · tg3** an invariant, inter- and intra-levels of organization, fractal homothety law: on the whole Universe scale (*down right black frame*, all levels of Fig. 7b), as on the scale of the Universe sub-systems parts (*top left green*, *red or blue arrows* in the enhanced frames of lower neighbouring levels), as in a scale beyond our Universe (upper neighbouring level), as well when we go down (*top left*) as when we rise (*down right*) in organization, whatever the degree of fitting (integration) and juxtaposition (organization), whatever the place of the local or global actors, the same exponent **3/2 power-law** (in the same log-log plot) "binds" the time of generation (***tg*** the duration of acquisition of the reproductive capacity) and the adult volume ***VA*** (volume at the end of the grown-up state) (Fig. 7a). (Reproduced and adapted from Bricage (2009a, 2014e, f) [Free Share-Alike Creative Commons Licence])

-in a no-change EXO- the maintenance of both a requisite variety of partners and the unity of the Whole. If the ENDO or EXO ever changes, that is the only way to set a new networking mode of organization and integration. These associations emerge through the interactive fitness between 'the capacity to welcome' of the EXO and 'the capacity to be welcome' of the ENDO of each parcener. Failures of medical

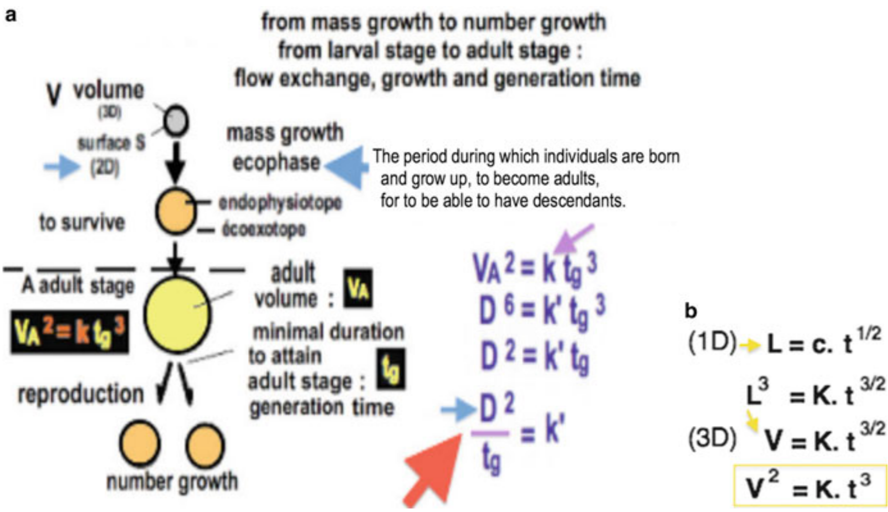

Fig. 9 *Exchange optimization at constant flows and Brownian motion:****"independent of mass and entropy relationship optimal surface flows".*** **a** Exchanges at a constant rate**t** time, **V** volume (**3D**), **A** adult phase, **D** linear dimension, **D2/t** flow per surface unit: a constant exchange rate **k′**. To survive with **mass growth** is the prerequisite for a life form to itself survive with **number growth**. **Just-in-time exchanges**: the exchanges flow rate at the surface of exchange is a constant. **b** Brownian motion. The length of the linear movement (*1D*), **L**, is proportional to the square root of the duration of observation -time **t**- (Perrin 1908): **1/2** power-law. This is the same as: **V** obeys a **3/2** power-law of **t**, or **VA2 = Ktg3** and **3/2** is just the true exponent that describes ***"the ratio of volume to surface area in a sphere"***. (Reproduced from Bricage 2009a, b, 2014e [Free Share-Alike Creative Commons Licence])

treatments and pathological processes can be explained in terms of breakages of time architectures. Inside a system, time can stop, move with different speeds and jump from one step to another but will never turn back (Bricage 2013b). When a step is in the past, a complete new cycle is needed to reach it again.

The Earth climatic phenomena (biosphere, macroscopic level $i + 3$) obey a power-law. The "life expectancy" of a phenomenon (in years) is proportional the **5/3** power of its size (radius in km). The "duration of survival" (in years) of an international institution (human species, macroscopic level $i + 1$) is proportional to the **1** power of the number of its members (like the mass and density into an ecosystem). Thus duration (time) is bound with mass growth (Fig. 7b) or size (volume) and number growth (Fig. 10b). Space and time interactions depends on mass that allows the implementation, through a percolation process (Fig. 4), of a temporal organization in a given space or/and a spatial organization at a moment and for a while.

Thermodynamics laws define temperature, energy and entropy, the physical quantities which allow to characterize living systems thermodynamics. The first law says that the energy (as matter, heat, or work) of a closed system is invariably preserved. Energy can change only in open systems, by transfers of external or internal origins. But the Universe is not a closed system: its fractal law of growth

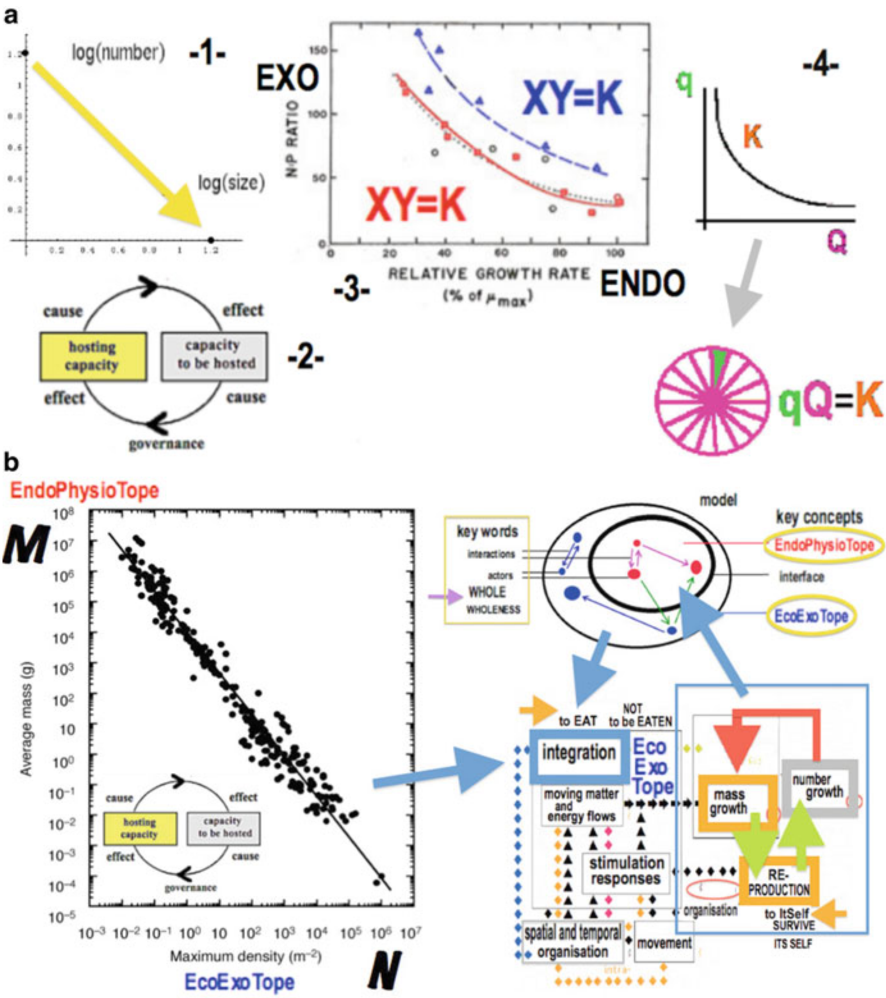

Fig. 10 Limits and limitations. (**a**) (*top*, from *left* to *right*: -1, 2, 3, 4, 5-) *"interaction is integration, integration is interaction"*. Rarely cause(s) and effect(s) relationships are linear, but frequently laws are power-laws, that are lines with log-log plotting **(-1-)**. Even we do not know which are causes or effects (systemic constructal law **-2-**) we can know what *local* actors are involved and what is depending/originating from **ENDO** or **EXO**. Often ENDO-EXO relationships obey a hyperbolic law, **XY = K, ENDO × EXO = constant**, whatever causes or effects (**-3-**). YX = K laws in log-log plots give a line as power-laws (**-1-**). Hyperbolic laws (**-4-**) like **qQ = K**, where q is the *'load'* of a *local* part and Q the *global* number of parts (**-5-**), are hallmarks of functional limits and limitations, with q for quality, Q for quantity we get ***(quality) × (quantity) = constant*** a known ecologic and economic relationship. Power-laws are hallmarks of **fractal** functional structures (Fig. 8). (**b**) (*down*, from *left* to *right*) *"gauge invariance parameters interactions"*. ENDO growth (**mass M**) is always limited by EXO HOSTING, shared by numbered partners (**density N**), the limitation rule for integration obeys a hyperbolic power-law **MN = K**. Mass growth **VA** is the limiting factor for acquisition of the reproductive adult stage (Bricage's diagram) (Bricage 1991, 2000a, 2001b). (Reproduced and adapted from Bricage 2010b, 2011 [Free Share-Alike Creative Commons Licence])

of **3/2** power (Fig. 7a) indicates that, as all the ENDO sub-systems which live in it (Fig. 8), the Universe ENDO "lives" in an EXO of survival which it shares with other Universes. The second law indicates that the entropy of a not in thermal balance closed system can only increase, its final steady state being that of maximal entropy. Soon or late it would reach a state where the energy would uniformly be distributed, without exploitable thermal differences for a work, the absence of available energy would not any more allow to maintain the energy-consuming processes of survival. The Universe expansion converts its available energy in work and heat, globally its thermal uniformity increases, but, using matter and energy to obtain a maximum production of organization (Fig. 8) for a minimum entropy production. Because it is an opened system, its order can increase.

The juxtapositions and embedments of the parts into their Whole are known (Fig. 6b) but the functioning of the Whole is not predictable from the functioning of the parts. The modularity of the actors and interactions is the source of exaptation and we have to define its parameters (Figs. 7 and 9).

4 Dynamics of Evolution and Evolutive Dynamics of ARMSADA Emergence

Storing a sufficient mass is a prerequisite before to become adult. The growth phase duration is the time of generation **tg**. Only mass growth, **M** (Fig. 10b), allows **3D** space growth (**V**), volume expansion. So it is not surprising to evidence a relationship between **tg** and **VA** (Figs. 7 and 8). The surprise is that this relation[2] is the same ($\mathbf{VA} = \mathbf{Ctg^{3/2}}$), scale invariant whatever the real, or virtual (Fig. 7a) levels of modelling (Fig. 6a). Mass is a limiting factor for expansion into space (Englert 2014) and for emergence of an internal time–space calendar (Figs. 4b and 5a) (Bricage 2013b, 2015).

The ARMSADA **inter-**merging process (Fig. 6), making from different species a new one, by embedment and juxtaposition, is an **intra**-emerging synchronizing process (Fig. 5), a percolation **extra**-emerging one (Fig. 4) with threshold and delay (Fig. 7b), like the timing mechanism that is involved in **intra-**organism differentiation at the cell level (Bricage 2013b). **Duration** is important but, soon or late, only small structural changes in **space** may be sufficient to trigger the **reciprocal interactions** that allow the emergence of an ARMSADA.

Integration is depending both on the actors' age and stage, their interactions and the Whole.

Connectedness in a network shows a threshold behaviour: at some point, the addition of a few more connections (Fig. 4a) can cause a substantial fraction of the network to be connected.

[2]The exponent **2/3** or **3/2** depends on which measure, **VA** or **tg**, we suppose as cause or effect, but we have no reason to think one could be rather a cause or an effect more than the other (systemic constructal law).

4.1 *Functioning of Functional Networks: "To Eat and Not to Be Eaten"*

Whatever the organization level, living systems must first acquire mass, from energy or other mass producing and stocking up systems (Bricage et al. 1990). To survive a living systems must "to eat and not to be eaten" (Bricage 1976, 1991). But, soon or late, every one is eaten (Bricage 2000a, b, c). The only way to soften partly the struggle for life is to enter into an **ARMSADA** (Bricage 2002b, 2005b, 2008) (Table 1).

Collective behaviours, through the emergence of complex migration patterns over scales larger than those of the local actors constituting a system, play a pivotal role in regulating various biological global processes, like gastrulation (movement), morphogenesis (reaction to stimulation) and tissue organization (into space and through time). Cell density (crowding), strength of intercellular adhesion (cohesion) and ***boundary conditions imposed*** by extracellular ***closure constraints*** (Bricage 2005a) are together involved in regulating the emergence of collective normal or pathological behaviours (Bricage 2008) into epithelial cell sheets. The geometrical confinement of cells into well-defined volumes induces a persistent, coordinated and synchronized move of cells that depends on cell density. The speed (X1) of such large-scale movements slows down as the density (X2) increases ($\mathbf{X1 \cdot X2 = k}$), an hyperbolic law, at the MICRO-scopic level, like that of the ENDO mass growth dependance on the EXO density sharing $\mathbf{M \cdot N = K}$ (Fig. 10a) at the MACRO-scopic level (Fig. 6b). Such collective behaviours depend on the micro-patterned volumes size V (a rotating motion of the overall cell population in a same direction is observed for sizes up to 200 μm). The rotating cells (***i*** level) move as a solid body, like an organism ($\boldsymbol{i+1}$ level), with a uniform angular velocity. This upper limit leads to length scales (k2, k3 of Fig. 7b) that are similar to the natural correlation length observed for unconfined epithelial cell sheets. This behaviour is altered in cancerous cell types (Bricage 2008). The governing stimulus is food: to survive that is first to eat!

The longevity (Maximum LifeSpan, in years) and body mass (in kg) of Mammals ($\boldsymbol{i+1}$ level) obey a power-law of exponent $+\mathbf{1/5}$. The women age of puberty (**tg**, age of acquisition of the adult grown-up state) is reached only after the acquisition of a minimal body mass (during the juvenile phase of growth, duration **tg**). If her mass gets down below this threshold the female loses, as long as her mass is too low, the capacity of reproduction. The females harem size of birds males is related to the sexes volumes ratio according to a $+\mathbf{2}$ exponent power-law, the bigger the male, with regard to the females size, the bigger his harem. Why? Because reproduction has a cost which is "paid" by growth. "The achievement of a volume threshold takes time." "Mass growth allows to change space-time scale" (Table 1).

Every ARMSADA emerges when the partners simultaneously lose the capacity to kill the other(s) (Table 1). In the new Wholeness, all that is an advantage for a partner is a disadvantage for all the others. The "parceners" are fused together "for the best and for the worst" (Bricage 2003b). The benefits are only for their Wholeness which expresses new emergent abilities (Bricage 1998).

4.2 Topology of Topological Networks. ARMSADA: Take-Make-Waste-Recycle, Waste Products From Ones Are Food Substrates for Others

EXO **hosting capacity** changes result in ENDO **capacity to be hosted** changes, and mutually. Each living system-of-systems is integrated into an ecoexotope within which it is more adapted to the interactions network than other systems-of-systems are (Fig. 4) (Bricage 2010a).

Actors interactions between and within organization levels are both causes and effects of flows of matter, energy and information (Fig. 9a). Each effect has a cause and each effect is a new cause for a new effect (systemic constructal law). Climate changes, communities changes of the EXO and ENDO changes are overlapping and in a loop (Fig. 2b2).

The EXO HOSTING changes, in quality or quantity (Bricage 2011), particularly due to recycling (Bricage 2010a), are controlling the growth and constrained changes in the functional, spatial and temporal organization of ENDO HOSTED. That feedback is controlling the growth and development (Fig. 7b, Table 2): ***(hosting capacity)*** $\times$ ***(capacity to be hosted)*** $=$ ***k*** (Fig. 10a). Step by step (Fig. 6a), by cycling through amplifying loops (Fig. 3b), "***a threshold of growth is a requisite for development, a threshold of development is a requisite for growth***" (Fig. 7b).

4.3 Temporality of Temporal Networks: An Optimal Full Surface Flow

ARMSADA: an "independent of Mass-Entropy relationship optimal surface flows"

The **3/4** power-law of metabolism, used to describe the **relationship between the size** of animal meta-cell organisms ($\boldsymbol{i+1}$ level) and their **resting metabolism** proposed by Kleiber (1932), printed in biology textbooks for decades, explained theoretically in 1997 and extended to all life forms in 2000, is wrong (Bricage 2014d, e, f)! It is **not 3/4 but 2/3**! That is just the true exponent that describes "***the dimensional ratio of surface area to volume in a sphere***", which surface increases as the square (2D) of the radius and volume as the cube (3D) (Fig. 9b).

The point of resting metabolism is to keep the body warm (and alive!) **with the lowest necessary energy use**, thus both geometry and common sense suggest a rate of +2/3. A no-spherical system, with more surface area relative to its volume, will lose heat faster and consume more energy. But the 3/4 (=0.75) and 2/3 (=0.66) slopes are very close to each other. And statistical analysis is very tricky with a lot of uncertainty in the parameter estimates (Fig. 7a). It is more easy to distinguish 3/2 (=1.50) from 4/3 (=1.33), so it is better to represent as power-law $\mathbf{VA = Ctg^{3/2}}$ rather than $\mathbf{tg = KVA^{2/3}}$, but the important fact is that such a relationship is related to the Brownian motion process (Fig. 9b). We must first qualitatively estimate the parameters for the quantification of complexity into the system, on its global context of interaction and on its local fate (Fig. 3a).

5 Discussion

To survive in order "to itself survive its self" limits and limitations: "You cannot eat the pie and have the pie"

With data from birds and mammals, the slope of the metabolic scaling relationship, approaches **1** at the lowest and highest metabolic levels, whereas it is near **2/3** at intermediate resting and cold-induced metabolic levels. These independently evolved taxa show a similar relationship between the scaling slope and the metabolic activity. Thus variation of the scaling slope is not a noise, but the result of physical **constraints** whose relative influence depends on the metabolic state of the organisms being analysed (Glazier 2008). What are these constraints? For adult males populations of *Pseudococcus maritimus* (Bahder et al. 2013), the regression curve in Log-Log plot between the variance and the mean gives a slope of **3/2** (with $P < 0.001$ and $r2 = 0.963$).

The relationship between the biodiversity (number of species) of an ecosystem (organization level $\boldsymbol{i+2}$) and its number of available "***ecological niches***" may obey a 1/4 power-law (Takeshi et al. 2015), but in a lot of wild ecosystems the relationship between traits of actors that are involved in the system's durability obeys **a power-law of exponent −1**, e.g. an hyperbolic law (Fig. 10a). Ecology is the economy of nature. Is it a surprising fact that ecology and economy may obey the same hyperbolic laws (Bricage 2014c, g, h)? Mass value is a cause of the growth phase duration tg, it is necessary to reach a minimal mass (Fig. 7b) to acquire the capacity to live on. Mass ENDO (Fig. 10b) is depending on HOSTING, but it also results from HOSTED, which determines the use of HOSTING EXO facilities. Mass value is also the effect of the HOSTING × HOSTED interaction. The growth phase duration is then a cause of mass storage. The body volume (VA) of an ENDO is linked to its mass and shape, it is limited both by the growth phase duration and the **constraints of closure** of its spatio-temporal interaction field. Depending on an arbitrary point of view (systemic constructal law), the volume VA can be the effect ($Y = f[X]$) or cause (X) of the phase growth duration tg (X or $Y = f[X]$). In their actions or effects, the Brownian motion, in a spherical volume VA in a time of birth of an organization tg (power-law $VA = f(tg)$ of exponent 3/2), or the temporal run (power-law $tg = f(VA)$ of exponent 2/3) and the exchanges phenomena at the surface of a sphere (surface to volume ratio of exponent 2/3, or volume to surface ratio of exponent 3/2) are equivalent (Fig. 9). VA and tg are ENDO limitations caused both by the HOSTING EXO limits and the HOSTED ENDO limitations, tg is as much a limitation of VA that VA is a limitation for tg.

The local actors become mutually integrated into their global Whole through their merging into an **ARMSADA** (Association for the Reciprocal and Mutual Sharing of Advantages and DisAdvantages) (Bricage 2010a, 2014b). Reversely (systemic constructal law), the global Whole is integrating the local parceners. As all the sub-systems which live in it (Figs. 1 and 6), the whole Universe is living in an ecoexotope that it can share with other Universes (Bricage 2014e, f). At every level of organization, the living systems evolution obeys a same organizing principle of emergence: the space (the volume of the adult system **VA**) and the duration (time of generation **tg**) are linked through a power-law of growth (Fig. 7a) and exchange (Fig. 9a) $\mathbf{VA^2 = C \cdot tg^3}$ (Fig. 8a, b).

Metabolic scaling is no more a consensus or a controversy (Agutter and Wheatley 2004), we do not need to take into account metabolism but only shape and exchange flows (Bricage 2014f) (Fig. 9a). Making an ARMSADA (Table 3) is the key process for building new blue-prints. When freed all the available places in all ecoexotopes are occupied. Each ecological niche results from a specific interaction, a co-constructive percolation process (Fig. 4) of integration between the HOSTING of the inhabited ecoexotope and the HOSTED of the inhabiting endophysiotope (Figs. 1b and 2b1) (Bricage 1976, 1982, 2011). Making an ARMSADA is like passing an exam for emergence and an examination for preservation (durability). And every life form has to pass it firstly and back indefinitely. For our species survival (Bricage 2011) we must take this lesson in application both in governance (Bricage 2003b, 2004, 2010a, 2014g) and economy (Bricage 2014c, g, h)!

6 Conclusion

Any systemic approach is functional: any alive system is an **ecosystem of ecosystems**, whatever its level of organization it is defined by the inseparable interactions between its endophysiotope and ecoexotope. The **ecoexotope** (exo: external, tope: space-time, eco: of housing), its home, supplies accommodation facilities for its body, the **endophysiotope** (endo: internal, tope: space-time, physio: of survival and reproduction), if and only if this one possesses a capacity to be welcomed (HOSTED) fitting with the accommodation facilities (HOSTING). Any alive system is known through its modularity (Bricage 1986): whatever its level of organization, it emerges by fittings and juxtapositions of pre-existing systems (Bricage 2001b), it is marked by its ergodicity (cybernetic approach). Any system is both opened and closed: properties depend on its functioning at interfaces (Fig. 9a), on its "transfrontaliérité" (Bricage 2005a); it is always both more and less than the sum of its parts (systemic and cybernetic approaches) (Figs. 4 and 5).

The huge diversity of levels of organization (Figs. 1 and 6), of living forms hides similar mechanisms (Figs. 2b, 3b, and 4). With the help of new concepts (Tables 1 and 3), -which had resulted to applied predictions: anti-HIV curative vaccine (Bricage 2005c), anti-cancer curative vaccine (Bricage 2008)-, a meta-analysis has allowed to highlight systemic laws (Table 2) which rule Life evolution (Bricage 2014d, e, f).[3] Any living system, to survive and live on, whatever its spatio-temporal level of organization (Fig. 6), owns seven invariant qualitative capabilities, seven degrees of freedom (Fig. 2). It is always formed by embedments and juxtapositions of pre-existing systems (Fig. 1). The local quantitative laws of its spatial-temporal structuring and functioning (Figs. 5, 6, and 7) are associated with these qualitative characteristics (Fig. 2) and independent from the dimensional scales (Fig. 6). Living systems are both independent and dependent from their new global level of organization and the local invariant (Table 1, Fig. 7) situations of emergence (Bricage 2014d).

Maybe we cannot **promote innovative and unconventional health, ecological, economical and social responsible, local and global, solutions** (Bricage 2014c, h) without the use of applied software tools. But words, concepts, paradigms, models and software tools, whatever they are helping to represent -chemical, physical, biological, mathematical or "universal" "objects"-, are only tools (Figs. 1, 2, 3, 4, 5, 6, 7, 8, and 9), not the reality. They are nothing without not only a comprehensive knowledge of biology (Tables 1, 2, and 3), through systemics and cybernetic approaches, but the respect of ethical ecological-educational-sociological-economical-political objectives (Bricage 2004, 2014a, g) to cope with the diversity and the complexity of our nature and nurture. Education is the key. **We first need teachers** to really allow the worldwide teaching of why and how man species may survive and in what manner and how we really can survive: between individualism and communism, in an agoantagonistic way "***For a Whole to survive, each of its parts must survive first.***" The systemic and cybernetic approach, through modelling, allows us to be the actors of "what we know and how we know it and how we represent it". That allows us not only to make predictions but also to know "what we do not know yet" about reality. Teaching is the action to promote operational practises, the way to balance and equilibrate theoretical fundamentals and applied research. We need ways of thinking simplexity (Berthoz 2009) rather than complexity elaborating tools. We need to shift from seeing the world as "stock and flow" machines but as living ago-antagonist systems, with their robust rather than optimal strategies (Bricage 2014a)!

The world greatest challenge is not health but education.

Every life form has an equal value (Figs. 6 and 8). Obviously, biological models are key-actors of the reliance between disciplines (Figs. 1, 2, and 3), because biologists must explore life -through its diversity and unity- from the quantum

[3]**Table** 3 http://hal.archives-ouvertes.fr/hal-00130218. Accessed 6 April 2009.

anti-HIV curative vaccine http://hal.archives-ouvertes.fr/hal-00352578/fr. Accessed 21 Sept 2005.

anti-cancer curative vaccine http://hal.archives-ouvertes.fr/hal-00351226/fr. Accessed 31 Dec 2008.

Table 2 http://hal.archives-ouvertes.fr/hal-00423730/fr. Accessed 19 Nov 2009.

of Planck to the whole Universe, because each biological system -whatever is its organization level- is both more and less than the sum of its parts (Fig. 5b).

Not machine to man, but man to man **teaching is the first step** to prepare minds.

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