

Application for accreditation to supervise research (HDR)

University of Montpellier, LIRMM

Campaign 2019-2020

Participatory modelling and interactive simulation to support the management of the commons

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6 June 2019

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Synopsis of topics and research projects

As a researcher at CIRAD since 2001, my work focuses on participatory modelling. This involves establishing foresight approaches supported by models designed and used collectively. The aim is to design (1) tools and methods to facilitate the collaborative design of multi-agent models and (2) tools to foster interactions with a simulation to influence simulated dynamics. Beyond the tools, my experience in the field contributes to reflections on how to conduct modelling workshops with stakeholders, and on the role of modelling as a key component for interdisciplinarity. In contrast to conventional approaches, my research seeks to understand the advantages and limitations of simulator-based foresight studies. In doing so, I seek to contribute to ethical issues on how to engage stakeholders, as well as the social and political responsibility of the facilitator. Within the Green research unit of CIRAD, I provide input on issues such as the analysing tensions between environmental conservation and development, as well as the role of collective action.

As such, the *Cormas* platform for which I am responsible, has the triple role as i) a research tool to assist the participatory design of models to improve their uses through interactive simulation, ii) an operational tool on the field and in projects and, iii) as a learning medium in training sessions, such as summer schools and university courses (UnB in Brasilia, PUC in Rio, UdelaR in Montevideo, UCR in Costa Rica). I therefore coordinate the development of the *Cormas* Platform, which requires significant computer-based developmental and maintenance input for the platform to work in various situations (land-use, hydrology, aquifer and livestock management, etc.). Coupled with this, it is also necessary to ensure its international dissemination.

From a technical perspective, the reason for including UML diagram editors is to facilitate and accelerate model design and implementation. The simulation component addresses the dynamics of social and ecological systems, in particular by considering the implementation and use of new tools for interactive simulations (distributed simulations, information asymmetry, agent manipulation, backward simulation, sensitivity analysis, etc.). As *Cormas* is a free software, I work with the *Pharo* Community.

Based in Latin America for the last 14 years, I have worked on several research projects studying the topics of adaptation to climate change, deforestation, livestock farming, biodiversity management and water pollution. In Brazil, I have worked mainly in the Amazon region (modelling pioneer fronts of deforestation, ecosystem services, integrating agriculture, livestock farming and forestry, Varzea zones), but also on comparing poultry farming sectors and water supply problems in Sao Paulo. In Bolivia, I studied the socio-ecological impacts of the emergence of quinoa in the global market while, in Argentina and Uruguay, I developed models on the competition between soya and livestock farming and adapting cattle farming to climate change. In Central America, I have developed tools to address the over-use and contamination of water resources and I am currently setting up an automatic early-warning system for coffee rust disease at the regional level.

Aside from my projects, I have also helped numerous researchers and students to design and implement their models.

HDR Thesis

Participatory modelling and interactive simulation to support the management of the commons

1. Introduction: Seeking a common thread

My research work began prior to my thesis defence, in June 2009. It should be noted that my academic career has not been straightforward but has experienced numerous detours into various disciplines.

After my preparatory classes in veterinary science then my first years at university studying biology, I started to encounter modelling during my DEA (Master's degree) in bio-mathematics at Lyon. That year, I also became familiar with multi-agent modelling when I completed an internship at IRD (French National Research Institute for Development). The aim was to consider the concept of validating a model of traditional fishing in Senegal, developed by Jean Le Fur (Le Fur and Bommel 1998). I think it was at this point that my career in research really began. Indeed, natural resource management is a hot topic, especially in the current context, and validating simulation models remains a controversial subject that requires an epistemic perspective. After my DEA, I pursued these considerations through casual appointments at IRD and INRA (French National Institute for Agricultural Research). My supervisor, at the time, Sylvie Lardon, introduced me to geographical research on territories and agricultural processes. I subsequently became familiar with the concepts of an “points of view”, the fact that we interpret the same landscape differently and the way in which our “mind maps” evolve. Some aspects of these considerations were developed into models (Bommel et al. 2000; Lardon et al. 2000) and now feature on the Cormas Platform (Le Page et al. 1999).

Following a DESS (professional Master's degree) in computing, I began a first PhD thesis in computer science supervised by Jacques Ferber at LIRMM. To fund this work, I created a start-up business with a friend to develop a massive online video game hosting platform. Designed to publish games, the platform was based on a multi-agent paradigm and an interactive distributed simulation concept. The most popular system at the time, based on the X-Window system, was built on a client-server architecture and we developed a robust peer-to-peer alternative that we set up on the MadKit platform (Michel, Bommel and Ferber 2002). When I joined Cirad in 2001, I had to abandon this thesis (and the start-up) to focus on other subjects. I think that this was the moment when I fully entered the world of research, when I began working at the Green research unit and by happily rediscovering the challenges

of natural resource management.

In my opinion, CIRAD is an unrivalled research organisation that provides the opportunity to conduct interdisciplinary studies on tangible development challenges. As responsible of Cormas (the modelling platform of the Green unit), I have also been able to work on research on concrete cases in South Africa (Erasmus, Van Jaarsveld, and Bommel 2002) and in Reunion (Farolfi et al. 2003), as well as a new topic for me, environmental economics. In addition, I have spent considerable time in training for multi-agent modelling for thematicians who are often novices in computing. I also took part, with my colleagues, in establishing the ComMod Network (Companion Modeling, Barreteau et al 2003, Bousquet 2005, Étienne 2011) by studying ways to adapt tools and approaches to provide participatory modelling for socio-ecosystems (SES). This new field of research ultimately targets social learning, involving purely technical aspects as well as ethical issues and the posture of the researcher in modelling.

Buoyed by this range of experience, I resumed my PhD thesis on a new subject. It wasn't a conventional thesis, but rather an analysis of my previous work by proposing a methodological framework to conduct more rigorous multi-agent modelling in development situations. You will have gathered that my research began well before this second thesis, which should be regarded as a review of my work at CIRAD, both in the field and in teaching modelling.

It should also be emphasised that the Green research unit is a truly interdisciplinary unit and that modelling undertaken here involves working in teams covering various subject areas. Since 2001, I have also (happily) worked alongside several colleagues from CIRAD and other organisations. These include economists, geographers, veterinary scientists, law anthropologists, hydrologists, soil scientists, sociologists, political scientists, agronomists and a few computer scientists! I have also taught and run modelling workshops in several countries, such as France, South Africa, Egypt, Brazil, Bolivia, Argentina, Uruguay, Ecuador, Colombia, Costa Rica, Nicaragua, Guatemala, Honduras, Salvador and the Dominican Republic. The topics were also very varied, such as public policy and landscape processes, water management, the expansion of deforestation fronts in the Amazon, the effects of the poultry sectors, social and ecological dynamics in Varzea areas, biodiversity and sustainable development in the Amazon, access to land and water in suburban areas, the growth of quinoa on the world market, competition between livestock farming and soya, adapting livestock farming to climate change, drought and water quality and, finally, coffee rust disease. With all these topics, locations and themes, how on earth do you find any consistency?! I've felt on the verge of schizophrenia several times, like the time when I was completing an interview with a Trans-Amazonian highway livestock farmer on crop rotation systems, pasture quality and resistance and problems accessing markets. I had to answer questions at the same time from Cormas users on how to scroll through lists of entities in Smalltalk!

Despite the subject areas encountered, topics covered and geographical areas studied, there is a common thread as my work has always focused on participatory modelling. I've often tried to involve local development stakeholders in modelling workshops to support

renewable resource management. My thoughts therefore turned to whether it would be useful to start a modelling process (it's not always necessary), or to define objectives for the model, the choice of model-type to be used (ABM, System Dynamics, Bayesian networks, FCM, etc.), how to involve stakeholders in model design and simulation analysis, as well as ex-post evaluations of these processes. Although participatory modelling is currently a popular approach, or a “buzzword” as Voinov and Bousquet (2010) would say, it appears useful to analyse their strengths and weaknesses, to describe their steps and postures to take, but above all, to understand the ins and outs for effective support of the actors. Like V. Grimm, who wondered why individual-centred modelling has not sufficiently contributed to ecology (Grimm 1999), we can question the merits and effectiveness of participatory processes based on ABM to help stakeholders boost the viability of their socio-ecosystems (SES).

Consequently, this thesis does not describe a unique and tortuous path, but rather seeks to propose a framework for participatory modelling as SES modelling requires considerable expertise while the model designer, who also facilitates discussions, must keep a critical eye on the tools proposed and the processes employed.

2. Background: Participatory modelling for social learning and renewable resource management

2.1. The GREEN unit offers a unique approach to viability

Since joining CIRAD in 2001, I have worked exclusively in the GREEN research unit. Although it is considered to be a small unit, with an average of 18 researchers, I have never felt cramped as GREEN is primarily a multidisciplinary unit that has striven, from the outset, to promote collaboration between topics and disciplines.

The Economist and Anthropologist, Jacques Weber, created GREEN (*Gestion des REssources renouvelables, ENvironnement*, or Management of renewable resources and environment) in 1993 to address renewable resource management from a staunchly **interdisciplinary** angle and not by a technical agronomic approach. In his founding text, J. Weber explains that, “*Finalised research must not stem from disciplinary frameworks but instead from concrete problems that it reformulates into objects of research*” (Weber 1995). Taking the example of pastoralism, he points out that its future is “*as much a botanical issue as a husbandry, ethnological, sociological and geographical one*”. It is better to specify the research challenges together when addressing these types of subjects, then to subsequently gather input from relevant specialists. This doesn't mean everyone giving their opinion on the matter independently, but collectively finding a new way of dealing with the problem in question using a space for dialogue to facilitate discussion.

Involved research, that transcends academic disciplines, is needed to address concrete questions by really immersing oneself in a local area. As Weber points out, “*One of the likely reasons development projects fail is because they are based on the assumption that changes might be effected externally on social processes among groups of people which are*

predominantly focused on sector-specific objectives. Even when community 'participation' is required, this hypothesis still appears to retain an element of utopia". Indeed, the overriding pattern when dealing with challenges to food security or environmental degradation, is to propose 'top-down' resource management frameworks designed by large multinational companies, state authorities or specialists from various organisations.

Conversely, it is, in fact, by trials carried out on the field and with local stakeholders that the real development questions arise, which may require revising initial goals. The project should therefore not be seen as a development goal decided from the outside, but instead as a means of supporting changes in local stakeholder organisation and practices. Obviously, "*with this way of organising scientific research, each relinquishes something compared to their own criteria of excellence, but the outcomes of collective efforts are different and far richer than they would be compared to the sum total of separate input from each discipline*" (ibid.).

Indeed, some basic concepts should be defined to better explain the unique character and theoretical foundations that underpin the GREEN research unit.

Firstly, what do we mean when we refer to a **renewable resource**? The French *Encyclopédie Universalis* states that natural resources correspond to "various mineral or biological resources necessary for human life and its economic activities". This means natural elements that humans use and which provide actual *value* for human society, such as minerals, fresh water, fish, firewood and solar power, etc. The concept of *renewable resources* takes the previous concept and adds a dynamic dimension, in that it replenishes its stock over a short period, in human terms. As such, oil is not classified as a renewable resource as the transformation of biomass into oil took place over the Earth's geological life time. Some resources that were assumed to be inexhaustible, as was the case of sea fish in the 19th century, can run out when over-exploited by humans (regeneration rates lower than removal rates).

By defining the environment as belonging to no one person (Weber and Bailly 1993), the emphasis is on "relationships between people about things". However, these relationships stem from a *system of values* specific to each society which determines, for example, "that some part of nature is 'useful' or not, harmful or not, precious or not" (Weber, Betsch, and Cury 1990). Our societies therefore rank these relationships and whether a resource should be exploited using a system of values and not for their basic needs. The same applies to the rarity of a good or resource whose value is determined by a social selection (or a "constitutional choice", according to Elinor Ostrom, 1990). Furthermore, "if the unclaimed environment now has so much value, it is because it has become a scarce resource" (Durand and Antona 2013).

In economics, managing such resources is frequently addressed by seeking a **state of equilibrium** of stocks to exploit in a rational way. These stocks are subsequently represented by "black boxes" which we study only in terms of inputs and outputs, in the form of material and energy flows. For economists, the problem then consists of defining an optimal level of extraction to maximise their exploitation (the famous MSY or Maximum Sustainable Yield, Schaefer 1954). However, this way of considering renewable resources, at least in terms of

living species, excludes the behaviour of these organisms and the way they interact with their environment. Living organisms are not independent as they are subject to a considerable **variability** in biotic and abiotic factors but they also interact within an ecosystem. Yet, these management models are historically based on analysing a single isolated species¹. On the rare occasions they do include abiotic factors, they ignore the influence of other species present in the environment. Nor do they consider the effect of a reduced target population on the overall way the ecosystem functions. Bound by complex dependencies, the “optimal and sustainable” exploitation of a species may result its over-exploitation sooner or later. “Instead of searching for an optimum, it is preferable to develop adaptive strategies for natural variations as well as economic fluctuations” (Weber, 1995).

The concept of **sustainable development** is rooted in these black box models, representing the balanced exploitation of a resource. It nevertheless came to prominence in the Brundtland Report by the UN World Commission on Environment and Development, in 1987. The report explained that, “*sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*”. The emphasis here is on finding a balance and consistent yields. This concept of sustainable development, based on a vision of nature as a stock to manage in a balanced way, results in the design of this form of development in terms of preserving environments, while maintaining and restoring balances. The term itself is a polysemic concept and contentious, based on an ideological bias and a vision of the world that must be debated (Daré et al. 2008).

By contrast, GREEN raises the question of development in terms of managing interactions between economic and social variabilities and their natural counterparts in both space and time. Ecosystems are considered as a support for the economy and society, the economy being part of the social sphere. In line with research by Jean-Pierre Aubin (1991) on “viability theory”, this vision of development, defined as “**viable**”, conflicts with the image of the three equal and substitutable pillars that form the foundation of sustainable development:

¹ The Schaefer model (1954), for example, seeks to calculate the optimal number of boats in a fishing zone to catch an isolated population of fish at its highest yield. This model ignores environmental factors and their fluctuations, as well as the target species’ trophic relationships with other species in the ecosystem. As a result, it is a slightly more elaborate prey-predator model. Nevertheless, this model has been used for many years by regulatory agencies to take decisions on transferable catch quotas and fishing licences.

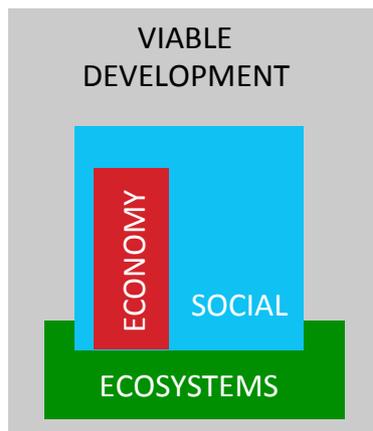


Figure 1: The place of the economy in viable development, according to J. Weber, Inaugural lecture, ESA

“Human life on Earth can survive even a severe economic and social collapse but it cannot survive a collapse of the ecosystems that feed society and as such, fuel the economy. The illustration of the three pillars implies that social, environmental and economic should be equal, but that’s far from the case. Ecosystems are the system that underpins life and the human societies that emerge from it, as well as the economy, only comprise relationships between people about things” (ibid.).

To address the issue of viable resource management, GREEN defined two areas of research, the first on decision processes and the second on modes of appropriation. Decisions are seen as the outcome of a process of interaction between individuals and groups of stakeholders having different weights in negotiations. The concept of “mode of appropriation” can be broken down into 5 levels: (i) the “values system” that societies bestow on resources, (ii) potential uses of resources, (iii) conditions of access to, and control of, resources (free or regulated access based on a wide range of rules), (iv) transferability of access rights, and finally (v), the way in which resources are distributed within a group by equal allocation, social status or based on market forces in western societies (Weber and Revéret 1993).

2.2. ComMod, companion modelling

“It should be acknowledged that on many points, farmers know more about the political economy than economists and governments”. Léon Walras

The conventional modelling approach consists of designing a model, adapting it to a reality with calibration data then validating it with other datasets. From this point, the model is considered as a decision-making tool (Bart 1995, Rykiel Jr 1996, Balci 1998). That said, we should be wary of this concept as there is a great risk of manipulating opinions. The sponsor of a model can rely on it when the results are in line with his position, or on the contrary, criticise its weaknesses when the results contradict a decision that he has already made (Boussard, Gérard and Piketty 2005).

A model is not neutral as it is the result of our interpretation of the world which gives meaning, as numerous psychological (Piaget 1968, Watzlawick 1978) and neurological (Damasio 1999) studies have shown. Whatever the type of model (descriptive or explanatory)

that we want to develop and regardless of our level of involvement in the subject, neutrality is impossible. The illusion of objectivity in modelling must be cast aside and we must “agree that all representation is partisan, not by any omission by the model designer, but deliberately so” (Le Moigne 1977). While believing they are distancing themselves from the world, “the researchers are part of the social circle and cannot detach themselves from it. The temptation is huge and this temptation is valid for each one of us, to think that it is possible to distance ourselves from the context and assess something independently from ourselves” (Ferber and Guérin 2003). Especially in the social sphere and the study of human behaviour, affirming one’s objectivity and neutrality is for a modeller an door open to all kinds of manipulation (Mullon 2005, Daré et al. 2010).

So, how can we make decisions that involve people in the process when the resulting statements are bound to be different from those of the decision-maker? How can we avoid the eternal pitfall of predictions? Decisions are often the “result of an interactive process between individuals and/or groups of stakeholders having representations and different weights in negotiations” (Weber and Bailly, 1993). To manage renewable resources in a sustainable and fair way, decisions are rarely the result of one decision-maker but rather the product of collective choices by stakeholders.

A solution lies in another way of addressing reality, an alternative form of simulation in which stakeholders play their own role, or that of another, to consider everyone’s point of view and incentives. This is the aim of the ComMod approach (*Companion Modelling*, ComMod 2005).

In contrast to a conventional decision-aid approach, the aim of the ComMod approach is to accompany the stakeholders to enhance the collective decision-making process rather than offer ‘turn-key’ solutions. Facing complex and dynamic socio-ecosystems (SES), subject to multiple uses, ComMod seeks to clarify each person’s point of view and subjective criteria. The process consists of designing a shared model that integrates the various representations. To facilitate the collective process, ComMod uses participatory modelling tools and role-playing games (RpG). Simulations and RpG help people gain a sense of perspective of an all-pervading reality. By taking a step back, people can discuss sometimes contentious or, even, taboo subjects (D’Aquino et al. 2003). By the stakeholders co-constructing the model, it becomes an object of mediation to resolve conflicts and take collective decisions. ComMod is therefore a **social learning** method (Le Page 2017) that gradually enhances knowledge by sharing and comparing everyone’s representations.

Before I joined Cirad, the ComMod network focused on a group of researchers from various institutions, but primarily from the Green unit. It published an inaugural charter setting out the founding principles to introduce the companion modelling approach. The charter was first published in English, in the *JASSS* review, entitled, “Our Companion Modelling Approach” (Barreteau et al 2003). A French version was then published in *Natures Sciences Sociétés* (ComMod, 2005). The charter specifies that ComMod has a dual purpose. The first is to understand complex environments in uncertain circumstances, i.e.:

- to generate knowledge on development challenges,

- to better understand the place and roles of stakeholders in the process,
- to co-construct universally suitable indicators.

With the inclusion of some entertaining games in the process, ComMod's second purpose is to facilitate collective decision-making, i.e.:

- to overcome moments when things are left unsaid between stakeholders,
- to facilitate exchanges and foster mutual recognition of different opinions,
- to provide an insight into collective issues,
- to facilitate and enhance the decision-making process.

In addition to generating individual and collective knowledge, ComMod nurtures each person's pre-existing interpretations to occasionally trigger changes in the ways people act and interact, or even modify stakeholder organisations.

An updated version of the charter ([Collectif ComMod] Bousquet et al. 2009) which I contributed to, emphasises the "Commodian's" posture rather than the process, by specifying the position of the companion modelling approach in relation to theoretical benchmarks (schools of thought in the sciences of complexity, convention theory, social learning, communication sciences, power games and mediation, etc.). As emphasised in my PhD thesis, this article highlights that a model is not neutral. It subsequently situates the ComMod approach in the *constructivist*² epistemology branch. By questioning whether ComMod is "a method to assist a group of people resolve a problem or to build stakeholder capacity to adopt protocols of interaction to foster adaptive management?", this article concludes that "the role of the person, or persons, that initiate the ComMod process is to help the gradual constitution of a group that will address this problem rather than identify a group and ask it to resolve the problem" (ibid.).

Companion modelling is used in this context, to perceive the model as an intermediate object: a **third-party mediator**³. By referring to Jacques Weber, we therefore understand that the "mediator is not seeking consensus, considered to be an unstable and unsustainable equilibrium. Its purpose is to foster an agreement on very long-term objectives, from which present challenges can be discussed" (Weber, 1996).

² Common sense would have it that our perception of the world stems from the nature of things. But, with Jean Piaget (1968), constructivists think that a person's representation is not a simple copy of reality, but rather a *reconstruction* of it. They demonstrated that the impression of evidence instead stems from the observer's cognitive and implicit construction. Understanding is constantly renewed and develops using older representations that are internally re-structured, mirroring the information received. These constructions are also derived from, and both formed from, the person's own system of representation specific to their culture (Friedberg, 1992, cited in Bousquet et al. 2009).

The first part of my PhD thesis develops the epistemological aspects to address the question of validating models.

³ "Mediation is a negotiating method that leads a neutral third party to facilitate agreements between participants. It helps express each person's views about challenges and problems so that they are understood" (ibid.).

3. Multi-agent modelling to simulate socio-ecosystems

“The aim is not to pit global holism implicitly against systemic reductionism, but rather to connect the substance of parts to the totality. One must connect the principles of order and disorder, separation and union, independence and dependence, that are in a dialogue (complementary, competitive and antagonistic) within the universe.”

Edgar Morin – The need for complex thought (1966-1996,
La passions des Idées, magazine littéraire, special issue, Dec 1996)

3.1. Schools of thought in sociology

In contrast to more conventional modelling techniques based on differential equation systems, multi-agent modelling offers a “bottom-up” paradigm connecting two levels: that of the agents and that of the entire system. Considering a social system in this way is part of a far older sociological debate that seeks to understand the decision-based choices of people rooted in their community. Here is a short overview of these schools of thought.

Methodological individualism

Raymond Boudon (1934-2013), subsequent to Max Weber (1864-1920), developed methodological individualism to analyse social facts. In it, he stated that social facts result from the actions of individuals accomplished according to their own values. Weber’s sociology, called “comprehensive” sociology therefore consists of understanding the reasons that push people to act in one way compared to another. Supporters of this school of thought consider that people have their own freewill.

The method therefore seeks to explain social facts in two stages:

1. “an explanatory stage to show that these social facts stem from a combination or an aggregation of individual actions;
2. an understanding stage to grasp the meaning of these individual actions and, more precisely, retrieve the right reasons why the actors decided to undertake them”, (Boudon and Fillieule 2012).

Interactions between people result in effects that are hard to predict. Emerging phenomena can be described by the appearance of a superior order resulting in individual, chaotic actions. For example, when people seek out their own personal interest in a market system, this helps meet the needs of all.

This point forms the basis of Mandeville’s “Fable of the Bees: or, Private Vices, Publick Benefits”, published in 1714. It illustrates the disconnection between individual activities and collective mechanisms. Mandeville, who was considered to be the precursor of economic liberalism, affirms that contrary to popular belief, “private vices” such as selfishness, contribute to the wealth of nations, while virtue condemns a community to poverty. The 1974

Nobel Economy Prize-winner and supporter of deregulation and privatisation, Friedrich Hayek, picked up on these ideas to explain market forces in his way: “[...] *in the complex order of society the results of men’s actions were very different from what they had intended, and that the individuals, in pursuing their own ends, whether selfish or altruistic, produced useful results for others which they did not anticipate or perhaps even know; and, finally, that the whole order of society, and even all that we call culture, was the result of individual strivings which had no such end in view, but which were channelled to serve such ends by institutions, practices, and rules which also had never been deliberately invented but had grown up by the survival of what proved successful*” (Hayek 1966). These same ideas provoked Milton Friedman (1976 Nobel Economy prize-winner) to state that “*the command economy is an emergence, the unintentional and unwanted consequence of a large number of people driven by the own interests*” (Friedman 1981). For supporters of economic liberalism, state interventions only hinder the “harmonious” mechanisms at work.

Although methodological individualism is often connected with the liberal movement because of its use by many neo-liberal economists, it should be emphasised that it is primarily an explanatory process to consider collective phenomena using single actions and individual attitudes. In principle, this approach needs no model for individual behaviour. It does not compel stakeholders to be “homo economicus” solely guided by maximising a utility function.

Methodological holism

A society exists from the sum of its parts, or individuals. While this is obvious, for holist sociologists, society transcends its component parts. In fact, it commands them. Proponents of radical holism believe that the individual does not determine society but is, in fact, entirely determined by society. Individuals are manipulated, conditioned by society’s structures and devoid of freewill. By employing a caricature, a delinquent cannot change to become honest as his social environment determines him to become a delinquent. Individuals are driven by social determinisms stemming from their social groups, social practices and collective representations. As such, we may not be able to understand an individual’s behaviour without considering his social group, family, as well as the customs and traditions of the community he belongs to.

Emile Durkheim (1858-1917), a spearhead of this movement (although the term “holism” was introduced later) sought to establish a scientific sociology by ignoring the psychological motivations of individuals. For Durkheim, the sociologist’s task is to distance himself from bias by looking beyond common sense, which has no scientific value. Each social fact must be studied using “Sociological method rules”. Emile Durkheim defines a social fact as “*manners of acting, thinking and feeling, external to the individual, which are invested with a coercive power by virtue of which they exercise control over him*”.

Durkheim takes the example of suicide, which he considers to be a fully-fledged social fact (Durkheim 1897). Instead of trying to explain using the suicide victim’s private life and mental state, Durkheim studies suicide rates based on social determinants. Using statistics, he showed that suicide happens when there is a lack of integration in a community.

Suicidal individuals are insufficiently attached to others and by integrating them, society, religion, family and the community protects them by morally forbidding them to commit suicide. In some political situations or public disorder, suicide rates tend to fall as individuals get involved in national matters that rekindle that sense of belonging to a society.

As such, while psychology provides a specific interpretation for each case of suicide, the sociological approach explains the frequency of suicide rates. “As such, given that causes vary according to individual or collective phenomena, there is no denying the existence of an independence or a methodological incommensurability to explanations of macrosocial phenomena. This independence is the focal point of the Durkheimian holistic approach” (Magni-Berton 2008).

Reciprocal dependencies

Other sociologists seek to transcend the dichotomy between the two schools of thought in sociology (holism and individualism). In his book, “The Society of Individuals” (1991), Norbert Elias (1897-1990) thinks that society is neither an independent ensemble that predetermines individual behaviour, nor the simple outcome of their actions. He explains that social phenomena result from interaction between individuals within a game where the rules are established. The individual subsequently has his own freewill, but his actions are influenced by those of others. These are reciprocal dependencies. The similarities between social life and a game arise because any action causes a reaction by other individuals. “*Like a game of chess, all action accomplished in a relative independence represents a blow on the social chessboard, which unfailingly triggers a retaliatory blow by another individual (on the social chessboard, whereas in reality lots of individuals trigger lots of reactions) limiting the first player’s freedom of action*”. The individual therefore has their own identity, but they are part of an environment of social relations that instil in them values, behavioural patterns, or a social *habitus*.

The habitus

For Pierre Bourdieu (1930-2002), each person’s place in society influences a type of behaviour. Each individual subconsciously internalises a *habitus*, a way of being, values and tastes. This habitus is acquired and determined from the individual’s social circumstances, i.e. from their economic, social and cultural environment. In other words, our social condition entirely guides our tastes and our *system of values* (see Weber, Betsch, and Cury 1990). While Bourdieu begrudgingly accepts a certain independence of the individual to change, their tastes and behaviour will influence his choices and priorities. For Bourdieu, the concept of habitus makes the connection between the individual and society. “Referring to habitus, infers that the individual, even the personal or the subjective, is social and collective. Habitus is a socialised subjectivity” (Magni-Berton 2008). Despite each individual’s own personal traits, the regularities observed in terms of individual tastes demonstrate belonging to a socio-professional category. By affirming that “everything is social”, Pierre Bourdieu speculates that everything has a sociological explanation (ibid.).

In doing so, he gravitates towards a more radical form of holistic sociology than Durkheim. In the latter case, sociology obeys its own laws. Even if they are derived from individual behaviour, they cannot, however, be explained by the study of individuals. “A social regularity emerges despite the contingency of individual choices and this is precisely the legitimacy of sociology” (Magni-Berton 2008). In Bourdieu’s case, methodological holism is more radical as it affirms that individual behaviour can be explained by the whole. “As such, individual tastes do not explain social order, but rather social order explains individual tastes” (ibid.).

3.2. The positioning of ABM in relation to schools of thought in Sociology

The multi-agent modelling seen as a social metaphor appears to have great merit (Livet, Phan, and Sanders 2014 give an in-depth review about this). In particular, the connection between individual and collective levels addresses changes in scale, a consideration that seems vital to understand specific phenomena. Developing artificial worlds in which agents evolve and interact, opens up definite scope for investigation. We subsequently define ABM as “constructivist approaches⁴” to rebuild the overall behaviour of a system by focusing only on the behaviour of individuals. As such, in “*Growing Artificial Societies*”, the renowned book by Epstein and Axtell (1996) which is a landmark in the multi-agent simulation community, the authors show that numerous social science-related concepts can be explained from simulations based on relatively simple models⁵. They pose the problem of “*How does the heterogeneous micro-world of individuals behaviors generate the global macroscopic regularities of the society?*” One of the reasons for the success of *Sugarscape* is the model’s simplicity and its relative ease in repeating the findings⁶. We can therefore illustrate the micro-macro relationship in the following diagram:

⁴ Not to be confused with constructivism, an epistemological school of thought that I cover rapidly on page 10 (note 2) and more comprehensively in my PhD research (chapter 2).

⁵ To study the direct and indirect interactions between agents, the authors use the population dynamics model, *Sugarscape*. This uses the spatial distribution of sugar and spice resources that replenish themselves according to simple rules. Agents, called “Citizens” use these resources. In basic simulations, the agents spot and travel to the best places to gather the sugar that they consume to counter the effects of their metabolism. The virtual world that the authors have developed can be used to test out various assumptions on the appearance of social structures, such as migration phenomena, trade, crises and wars. Using simple representations, the authors subsequently try to explain complex social phenomena: “*Artificial society modeling allows us to “grow” social structures in silico demonstrating that certain sets of microspecifications are sufficient to generate the macrophenomena of interest. Indeed, it holds out the prospect of a new, generative, kind of social science*” (ibid.)

⁶ Several attempts to replicate findings have demonstrated the difficulties in reproducing the results (Lawson and Park 2000, Meurisse 2004, Michel 2004, Bigbee, Cioffi-Revilla, and Luke 2007, Axelrod 2003), difficulties that often turn out to be related to time management (see. section 4.5).

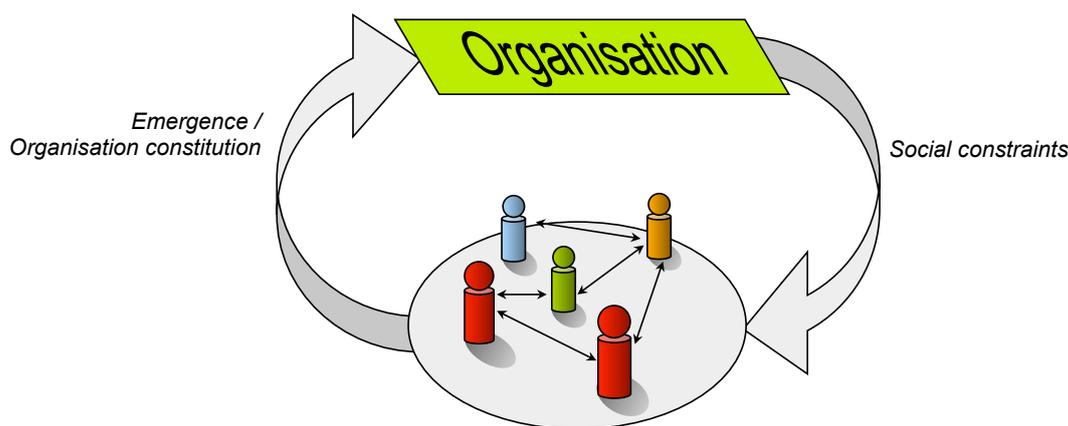


Figure 2: The micro-macro relationship in multi-agent systems, adapted from Ferber 1995⁷

“The power of ABM comes from this cycle: Agents act independently in a space constrained by the structure of the society in which they evolve, the structure, itself, resulting from the behaviour of these agents. We therefore find ourselves in a cycle of dependence between agents and agent society, between micro and macro levels, between the individual and the collective, who ultimately find themselves at the heart of the problem of complex systems in human and social sciences. [...] It is no coincidence, therefore, that ABM appears to be a key tool to model societies”. (Ferber 2006)

The debates between different schools of thought briefly covered in the previous section seek to understand the decisional choice of individuals rooted in their society. Consequently, do we act through individual freedom or by social determinism? Does the individual take precedence over the group (methodological individualism)? Or is it the opposite? Does the group usurp the individual (methodological holism)?

Given this rapid overview, we can, at first glance, position the agent-based modelling process as a paradigm stemming from *methodological individualism*. Most ABMs developed (with Cormas but also most of those developed using other platforms) initially fit into this framework, dispensing with sharing the political opinions of those supporting economic liberalism.

For example, a spatialised prey-predator model strives to describe the simple and “individualistic” behaviour of agents, without relating societal norms that constrain or enhance this behaviour. Simulations subsequently reveal population fluctuations. Here, the macro-level spontaneously appears. The “influence of society” does not determine individual behaviour as each agent retains their own freewill and is not manipulated by their belonging to a group. That said, actions by some pressure the survival of others. When a predator

⁷ This diagram provides a clear and succinct summary of the multi-agent paradigm. Nevertheless, I have identified a weakness in it. The organisation feedback to the agents is only expressed in terms of social constraints. Yet organisations and society channel other values, such as warnings, language and culture that permeate all individuals. In this case, it is positive feedback from the society to the agent. As Maturana and Varela (1994) point out, *“The human social system boosts the individual creativity of its component parts inasmuch as the system exists for the benefit of these component parts”*. The authors refer to these relations between individuals and the organisation as *“third-order coupling”*.

captures their prey, this has a direct impact of the processes governing the prey and indirectly on the survival of other predators by reducing the numbers of prey. Similarly, an overgrazed area affects an herbivore agent inasmuch as the actions of others affect it indirectly (i.e. through the environment), while the herbivore itself also unknowingly contributing to this situation.

This observation does not stop us considering that the way we perceive agent behaviour (the prey grazes while the predator hunts) stems from a perception of the world. Consequently, the perception of the modeller can be considered to be determined by their own social group. As P. Descola states, “*Any talk about nature is a statement of society*”. Clearly, this might appear exaggerated in the case of the prey and predator, but we should not ignore this consideration, especially when trying to describe human agents.

Multi-agent simulation is still under-valued by the social sciences despite appeals for greater ‘haste’ in sociological modelling (Manzo 2007, 2014b). In their analysis published in JASSS (Journal of Artificial Societies and Social Simulation), Squazzoni and Casnici (2013) show that the articles featured in the review have greater impact in computing, physics and ecology than in social sciences. In France, it was not until 2014 that the *Revue Française de Sociologie* (French Review of Sociology) published a special edition on “Multi-agent simulation: principles and applications for social phenomena” (Manzo 2014a). Yet, this effort barely changed the picture, as Bruno Latour and his colleagues explain,

“Simulating the emergence of macro structures from micro interactions has never been an optimal research strategy, neither methodologically nor politically. [...] Empirical studies show that, contrarily to what most social simulations assume, collective action does not originate at the micro level of individual atoms and does not end up in a macro level of stable structures. Instead, actions distribute in intricate and heterogeneous networks than fold and deploy creating differences but not discontinuities” (Venturini, Jensen and Latour 2015).

At best, very simple multi-agent models (KISS) help highlight implicit models, such as Schelling’s segregation model. Conversely, “when this approach seeks to explain reality by making models more complex, it encounters objections that I currently consider to be prohibitive” (Jensen 2015).

It should be noted that few agent-based models are derived on a formalisation of social determinism in which agents internalise social codes (as with the *Dricol* model) or, for that matter, Bourdieu’s habitus concept (as with the gift exchange model, Alam, Hillebrandt and Schillo 2005)⁸. BDI model architects could use these principles, but few models describe the internalisation mechanisms of social codes.

There is, however, literature on the subject, which Neumann (2013) reviewed. By describing how social constraints are considered in multi-agent simulations, he lists various models that address social norms, their distribution and internalisation by agents. He shows that only the development of cognitive agents addresses these questions and to “better understand the

⁸ We will see that Cormas provides tools to address the concept of habitus, not from an agent perspective but rather for the platform users, for interactive simulations (see section 5.3).

effects of normative behaviour constraints”⁹. He refers to the pioneering work of Conte and Castelfranchi (1995) on the subject, but highlights the lack of models addressing socialisation phenomena. Acknowledging the benefits of ABM, he concludes “*There is, however, still a lot to do with regard to achieving a comprehensive understanding of how actors produce and are at the same time a product of social reality. [...], it has to be decided whether an antagonism individual and society is assumed or not. This is the question, whether the social macro-level is perceived as action constraint or as enabling action selection*” (Neumann 2013).

That said, it should be acknowledged, along with Venturini, Jensen and Latour (2015) that social simulations cannot express subtle mechanisms which result in the emergence of common norms and social behaviour. They explain that family ties, reputation, compassion or facial expressions are vital for human relations. As conceptual models cannot capture these subtleties, social simulations based on ABM appear ill-adapted to reveal the complexity of social systems (ibid.).

I subscribe entirely to the idea that we are unlikely to reproduce all human faculties in a multi-agent model. I firmly believe this, as given the current state of techniques and knowledge, I think it would be futile to want to reproduce human cognitive behaviour as well as that of our societies. We cannot provide a model with the “degree of complexity required” (Erceau 1995) that matches that of human organisation. Given such a system, we are simply unable to match a cognitive model with a comparable level of complexity (Bradbury 2002). Nevertheless, I do not reject the use of modelling to understand forms of human organisation. Indeed, the aim is to use tools to test assumptions about a given reality, not to copy a social system. Regardless of its complexity, a model is nothing more than an abstract and provisional representation of an incommensurably more complex reality. Furthermore, this is not a technical limitation issue. Seeking to match an equivalent model with human organisation means considering that we can provide a *neutral* model with a level of complexity similar to *reality*, as if this reality was given to us in an objective way. In training sessions, I emphasise that a model is just a tool to try to understand a phenomenon. It is way of challenging our perceptions of a system by pushing logic to its most extreme consequences. During field work with various local stakeholders, I think it is necessary to desacralize our tools by indicating that the models are only mental ‘crutches’ to help people think.

As it stands, the multi-agent paradigm does not allow us to decide whether the individual leads the group (methodological individualism) or on the contrary, the group that takes precedence over the individual (methodological holism)¹⁰. At best, it does however address bi-directional interactions by attempting to understand how agents produce and are simultaneously the products of a social reality (Deffuant, Moss and Jager 2006).

⁹ Deffuant et al. (2003) explains that complex models are not necessarily more realistic than simple models. They add that BD-type architecture very commonly used to model cognitive agents is not always founded on a robust scientific basis and that they neither stem from the precepts of neuroscience, psychology and philosophy.

¹⁰ And this won't be the aim of my future research!

This cycle of dependence between micro and macro levels lies at the heart of the multi-agent paradigm. When emerging properties from an ABM become visible, when they indicate a new organisation (a pattern such as the path taken by ants between the nest and the food), we refer to *self-organisation* mechanisms (Holland 1995). A self-organised system is based on its ability to spontaneously produce a new organisation of a group of agents and the environment without external direction.

This organisation is sometimes referred to as an entity in its own right, with its own rules that influence and guide its behaviour and its components (constraints, conventional rules, etc.). When reflecting on “social beliefs”, A. Orléan (2004) defined the group as a social object, an abstract entity with its own autonomy in relation to the individuals comprising it. He uses the following phrase as an example: “The market thinks that this currency is under-valued”. Clearly, the financial market, as such, doesn’t have the ability to think, but it has a life of its own that transcends the simple arrangement of those working in it, i.e. “From a historical and social perspective, communities are not just a collection of individuals as their identity is not defined by a list of individuals” (Descombes 1996). The markets cannot be reduced to a group of traders or analysts that play a role in it at a given moment. Instead, the markets continue irrespective of the comings and goings of those working in it”. This complex social structure therefore has a meaning and maintains itself over time independently of the financial traders and analysts that play a part in it and who exceed their individual dimension” (ibid.). based on the way an organisation is perceived, it could be represented as the outcome of interactions between entities or, if we give it a certain autonomy compared to its constituent parts, it can be modelled as an agent.

However, generally speaking (and it’s what we recommend in our courses), the modeller must strive to only represent individual behaviour when designing his ABM, then reveal, with time and interactions, the emergence of global phenomena. As such, agent-based models belong to the *methodological individualism*, even if though they do not defend the conclusions of supporters of economic liberalism¹¹.

To conclude we must emphasise that one of the basic principles of ABM is interaction. This refers to interaction between agents and interaction with the environment. The multi-agent paradigm can then be considered to belong to Norbert Elias’ “*reciprocal dependencies*” school of thought. Although each agent has their own freewill, their actions are influenced by

¹¹ On this aspect, J. Weber developed a small learning model to demonstrate that a deregulated economy does not regulate itself, contrary to what Adam Smith’s “invisible hand” might say, as well as prevailing neoliberal rhetoric. The agents in his model (*PlotsRental*) are farmers who own fields scattered across an area. The greater the distances between fields, the more their productivity drops. To reduce these distances, they try to exchange fields between them. Two methods of exchange are then tested: 1) a “mutual agreement” method resulting in a transaction as soon as it appears beneficial for both agents and 2), a “centralised” method in which an official receives all offers of possible exchanges, then after sorting them according to level of interest, sends the most attractive offers to the farmers concerned. In contrast to the mutual agreement method, the centralised option obviously results in an optimal rearrangement of the fields. To secure the same outcome using an non-centralised method, “we should imagine refinements that can be assimilated to regulatory mechanisms” (Le Page and Barreteau 2013).

those of others. One action can result in a reaction from other agents, as is the case with numerous multi-agent models.

Before closing this part, I would like to mention the work of cognitive science pioneers, Francisco Varela and Humberto Maturana, who, in the “The tree of knowledge” studied the organisation of living systems, from the simplest to the most complex. In presenting the concept of “third-order coupling”, which describes relationships between individuals and the organisation, they explain, in keeping with Constructivism, that the cognitive act is not the simple mirror of an external objective reality but rather an active process rooted in our biological make-up, by which we create our realm of experience:

“The world that everyone sees is not the world but one that we reveal with others. [...] We humans are only human by language. Because we have language, there is no limit to what we can write, imagine and tell. As such, language permeates our entire ontogeny as individuals, from the way we walk to our political persuasions. [...]

Spirit is not something found within our brains. Awareness and spirit lie in social coupling”
(Maturana and Varela 1994)

4. Cormas, a modelling platform to support the ComMod process

4.1. Origins and features of Cormas

Right from the beginnings of the Green research unit (see section 2), developing modelling tools to study interactions between stakeholders and resources in an SES was considered to be essential. Yet, given the direction of its research priorities, the Green unit did not want to use conventional economic tools that seek to maximise use against constraints and reason on balanced flows (see section 2.1). Instead, the choice was rapidly made to favour multi-agent modelling as this paradigm seems best-equipped to address human-nature society relationships, as explained in paragraph 3.2 (page 15). By avoiding the assumptions of dynamic general-equilibrium models and by reasoning on local-global relationships, ABM addresses renewable resource management with an interdisciplinary vision.

As such, from the research unit’s very origins, François Bousquet, Innocent Bakam and Hubert Proton (computer science students, at the time) came up with an initial version of the Cormas platform. Even then, its name referred to managing the commons. CORMAS is the acronym for “COMmon-pool Resources and Multi-Agent Systems”. It is a multi-agent modelling and simulation platform tailored preferentially to renewable resource management. Like *Sugarscape* (Epstein and Axtell 1996), The principles that guided the development of Cormas are based on a simple meta-model, providing spatial entities on which resources and agents capable of perceiving their environment locally are positioned. Cormas is intended to facilitate the design of ABM, as well as monitor and analyse simulations. Indeed, the purpose of a ABM is to understand how independent entities can interact, coordinate themselves and co-evolve, while generating effects on the system.

Cormas, is a free, open-source application, available on the Cormas website cormas.cirad.fr. The first version was published in 1998 (Bousquet et al. 1998) and was quickly adopted by an international research community keen to study relationships between societies and their environment. In 2012, we published an article in JASSS outlining Cormas' role in nurturing and enhancing a community of practice (Le Page, Becu, et al. 2010). This was because among the existing generic simulation platforms, Cormas occupies a small but unique and dynamic position. With its electronic forum¹², but especially training courses that we organise on a regular basis in various countries (see section 7), a community of users gradually took shape. This community makes it easier to share ideas, practices and knowledge and now there is a proper community of practice whose members are especially interested in agent-based participatory simulation.

4.2. Why Smalltalk?

Cormas operates on Smalltalk, one of the first purely object-orientated languages¹³. It uses VisualWorks (an application of Smalltalk first developed at Xerox PARC, then by ParcPlace Systems before being acquired by Cincom) (Brauer 2015). This is a programming language but also an interactive development environment (IDE) which is also written in Smalltalk. Instead of providing a script language, as is the case for several platforms (written in Java, Netlogo and Gama, which in turn use Logo and GAML), Cormas users must programme their models using Smalltalk. Cormas also has all the functions provided by Smalltalk, which opens a much greater space for potential than other platforms on the market.

Smalltalk is broadly perceived to be a moribund language and relic of the times, but this is far from true. It is, in fact, a high-quality language with a rare elegance to it. Despite its unique design, it continues to evolve. It is a reflexive, dynamically typed, object-orientated programming language. Smalltalk targets simplicity and efficiency. Everything is an object and its syntax fits on a postcard. All the methods are public, attributes private and its legacy simple. As with Lisp or Java, Cormas' memory is automatically managed by garbage collector.

More than just a language, Smalltalk is also an immersive system that allows introspection, reification and intercession¹⁴ to foster rapid prototyping of models. Its powerful debugger helps modellers check their model functions in great detail, but also to amend the code directly, even when running a simulation. Furthermore, debugging a programme is a learning

¹² The forum (cormas@cirad.fr) currently has 337 members.

¹³ Successor to Simula, Alan Kay is one of the object-orientated programming founders who, together with his colleagues, created the first version of Smalltalk-72 then Smalltalk-80.

¹⁴ The term, reflexive language, is used which enables *introspection* (to inspect and analyse any object in a system) and *intercession*, to amend the its semantic and behaviour within the language itself. In Smalltalk, the classes and methods are objects just like others. You can not only access information represented by these entities but also to modify and dynamically create instances for these classes (which isn't possible in Java) (Ducasse 1997). It is therefore a meta-programme able to handle other programmes including itself.

process in itself that takes the developer to the heart of their simulation and offers a more substantive vision of the way it operates. When a bug stops a programme running or when you position the completion point, a verification window opens and provides guidance to understand the problem. As a result, you can navigate in the code, monitor how objects evolve or create a method, then return to where the execution flow stopped. Some call this the “edit and continue” method instead of the traditional “edit, compile and run” method. I prefer “Live coding” and “direct model checking”. I often use this method to develop my models directly from the debugger.

Smalltalk is consequently an effective language to teach programming and object concepts to beginners in computer science. It is also a great language to prototype a model and check that it works.

4.3. Cormas structure and operation

Ever since I joined the Green unit, I have been responsible for the development of the Cormas platform, as well as coordinating the website and user list. My colleagues, Christophe Le Page and François Bousquet, are also involved in development activities. In addition, Nicolas Bécu (CNRS) and Bruno Bonté (IRSTEA) helped develop the platform. We subsequently train a small team that works more or less regularly on Cormas development.

Unlike the conventional development of IT software, the philosophy governing the development of Cormas has involved combining new functions based on needs from various projects and user requests. In the funding article (Bousquet et al. 1998), Cormas’ main interface is as follows:

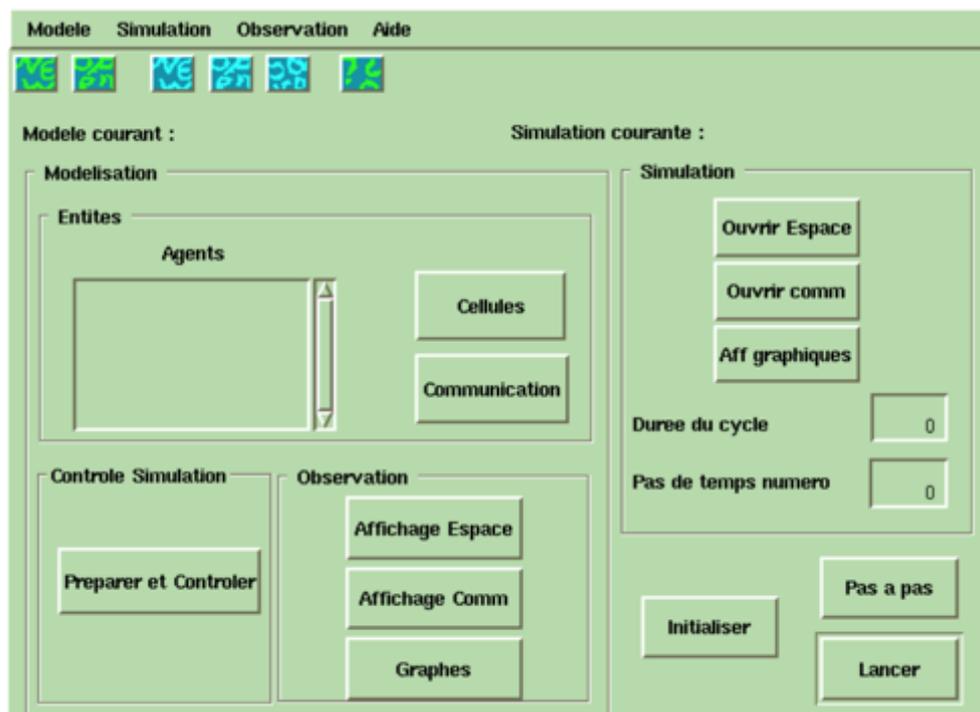


Figure 3: Initial Cormas interface

Two key concepts already feature on this interface: (1) the MVC¹⁵ pattern application which distinguishes the Model (the entities) from its observation (View) and Control, and (2) a structure that splits the entities into agents, spatial cells and communication channels. That said, this organisation of entities has been modified to be more in line with a simple diagram proposed by J. Ferber in his visionary book (Ferber, 1995) summarising the main concepts of a ABM:

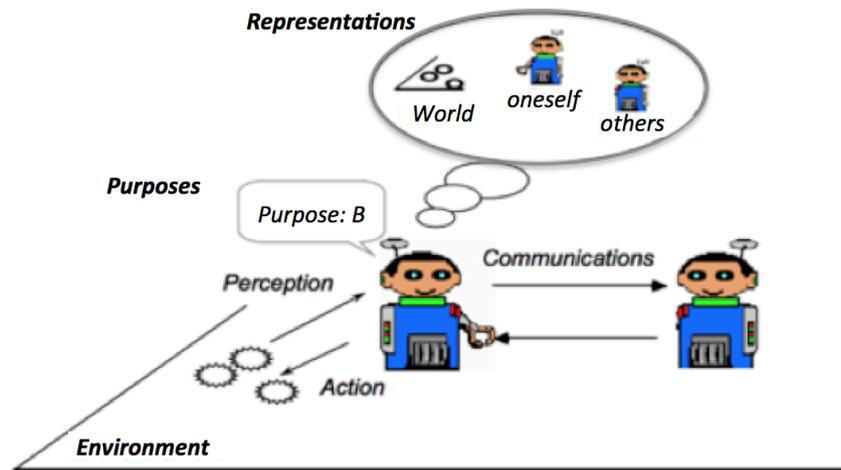


Figure 4 : Pictorial representation of an agent interacting with its environment and other agents and objects in the world, according to (Ferber, 1995).

This description shaped the development of Cormas whose structure still organises entities into three categories: 1) spatial entities, 2) social entities (agents) and 3) passive entities, such as those features on the interface of the first version available for download (Figure 5).

Cormas is a *framework* that provides predefined classes and a set of visualisation tools. This means that the modeller implements their model by specialising predefined classes. These contain attributes and generic methods that can be re-used by the specialised classes. There are basically three types of generic entities available: “social agent”, “spatial entity” and “passive entity”. So, to create a ruminant, for example, the modeller can define it as an *AgentLocation* sub-type. During a simulation, each new instance for this agent will be automatically recorded by the simulation organiser (the Scheduler). It will also be able to move around in space and perceive its neighbours by using generic methods (`#moveTo:` and `#perceive`) defined into the *AgentLocation* super class. The following class diagram shows how a simple ECEC¹⁶ model with two types of entities (Vegetation Unit and Forager) can be incorporated into Cormas.

¹⁵ MVC, (Model-View-Controller), is a software architecture pattern that specifies a clear divide between the model code and the way to visualise and manipulate it. Trygve Reenskaug, who worked at that time on the design of Smalltalk with Alan Kay, Dan Ingals, Ted Kaehler and Adele Goldberg at Xerox’s Palo Alto Research Center, designed this model architecture in 1979.

¹⁶ Designed by Pepper and Smuts (2000), ECEC has been replicated in Cormas. It is a training model to explain how an ABM works. By showing a simulation step-by-step, those unfamiliar with ABM can quickly grasp its mechanisms. However, despite its simplicity, its simulation results are by

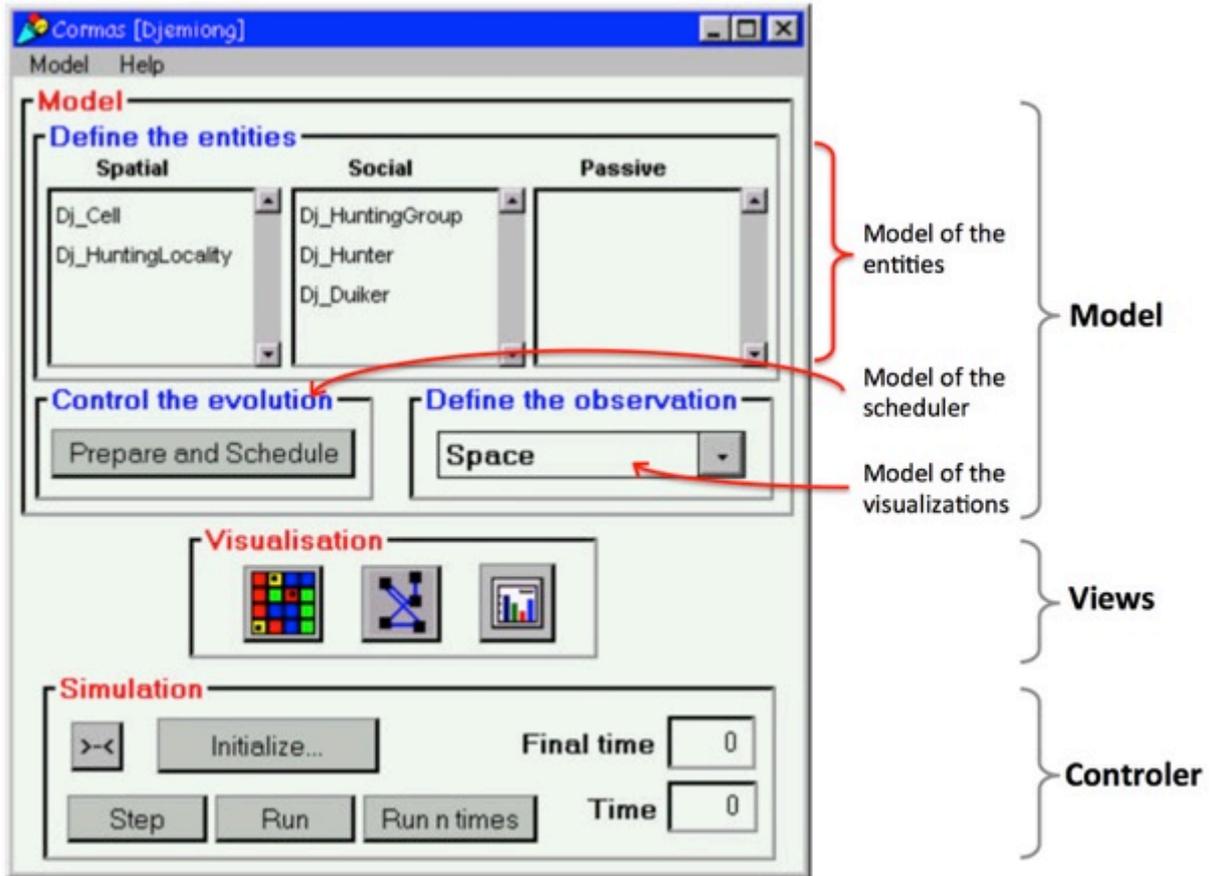


Figure 5: Cormas public interface, version 2, that forces the modeller to distinguish the entities of the world, from the way they are viewed and activated

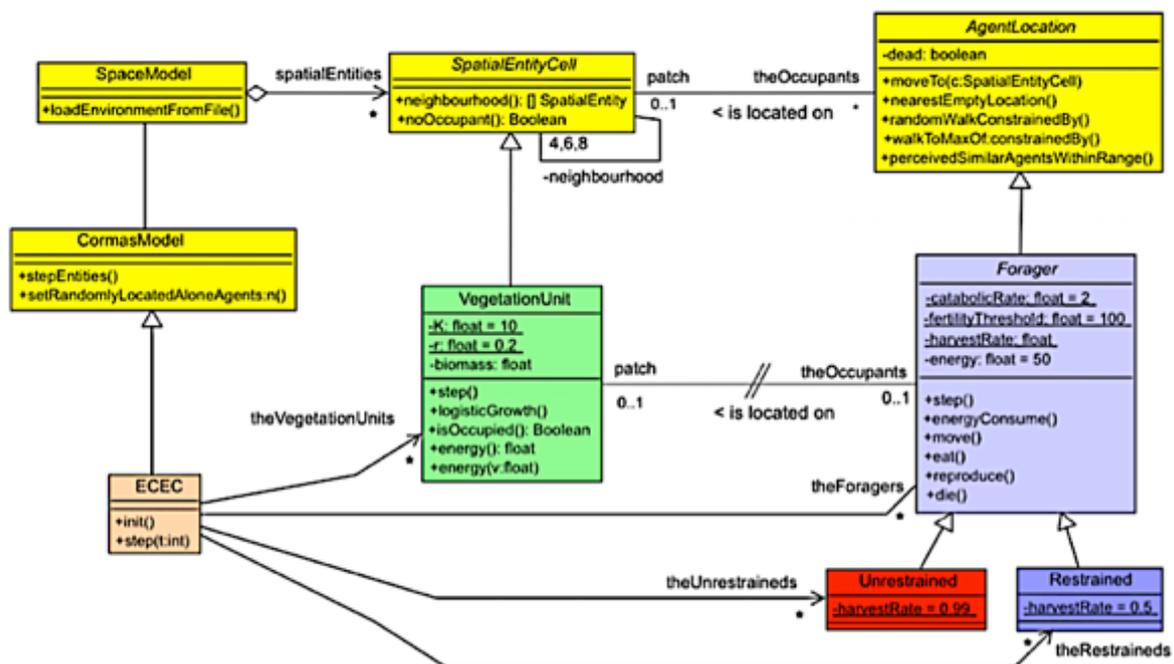


Figure 6: UML Class diagram showing how the classes in the ECEC model fit into the Cormas framework (yellow classes).

no means trivial. They can be compared to conventional ecology models, such as the Lotka-Volterra model or the Gause model (principle of competitive exclusion).

The *Forager* class (Ruminant) inherits useful, predefined methods in its super class, such as *#nearestEmptyLocation* or *#moveTo* that enable the instance of *Forager* to perceive free spaces around it and move to a given space. These generic methods can be re-used in the *#step* method to specify the agent's daily behaviour.

CormasModel is the model's abstract scheduler. It has to manage the overall control of the simulation dynamics. In this case, it is specialised by the *ECEC* class that can reuse many predefined methods for instantiating the initial state of a simulation and to activate the entities. To do this, the scheduler contains three attributes, each containing a list of instances of the concrete classes of the model (the green, red and purple classes in Figure 6). These attributes are set automatically when creating the model classes, while the list of instances is automatically updated at the end of each simulation time step (by removing dead agents and adding new ones).

The advantage of using a platform is that it frees the modeller from many coding constraints. As *Cormas* complies with the MVC architecture, it allows the modeller to focus solely on their subject without worrying about the accessories that come with a simulator. After having coded the agents and the other entities in their model, the modeller just has to specify the way the entities are activated by the scheduler. Finally, the modeller can choose the way he wants to visualise the entities and indicators of his model (Figure 5). Several interfaces are available for this stage that avoid coding the model display and the indicator charts. A colour, or range of colours, can be given to the value of an attribute or an operation of a spatial entity and a figure or image to an agent. Unlike other platforms such as *Netlogo* that require a colour or an image to be defined for entities into the model code, this decision to clearly separate the model code from its visualisation and manipulation is specific to *Cormas*. Apart from the fact that it focuses attention on the entities, it also provides a range of uses for the same model: changing points of view, zoom-ins, distribution, information asymmetry, agent manipulation, etc. (see following section).

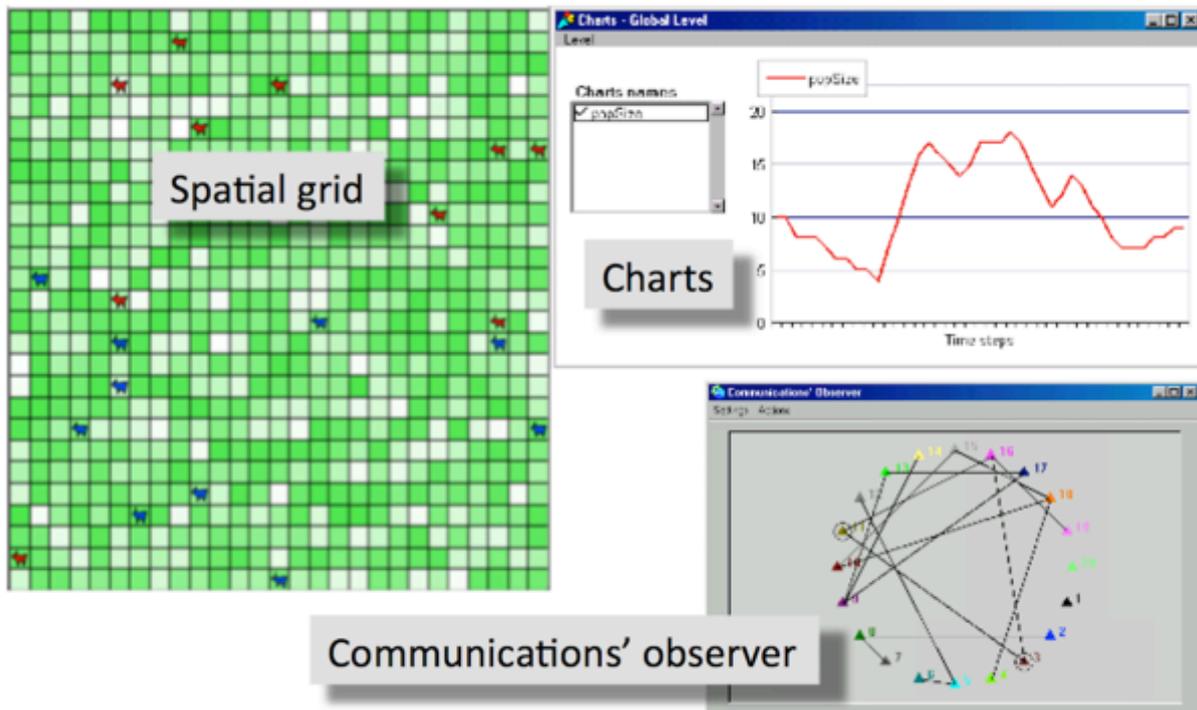


Figure 7: Three ways of visualising a simulation in Cormas

4.4. Agents, really?

To distinguish communication networks from agents (see “*Communications' observer*” in the figure above), Cormas provides the *AgentComm* class that comes with a *MailBox* and a communication channel (*Channel*). Without blocking the sending agent when sending a message, the channel is tasked with sending the message to the receiver inboxes asynchronously (immediate dispatch) or synchronously (delivered at the end of the time step).

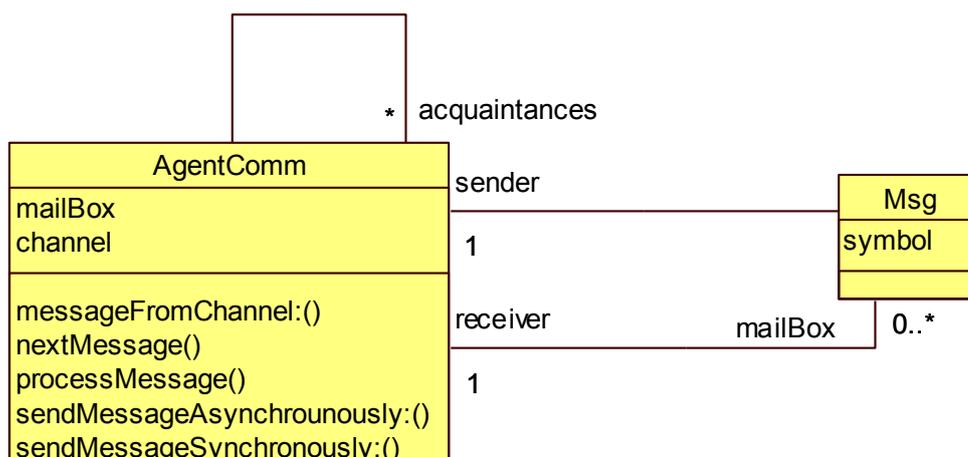


Figure 8: Diagram of communicating agent classes

In an effort to answer the question raised by (Drogoul, Vanbergue, and Meurisse 2003) “Where are the agents?”, these mechanisms were also designed to reinforce the difference between agents and objects, such as the concept of autonomy, reification of message sending,

asynchronism, conversation and language acts, etc. However, managing conversations between agents is not technically easy to ensure. Message sequencing for autonomous, threaded or distant¹⁷ agents, requires rules to produce a coherent discussion and follow the proceedings over time. Several attempts at normalising inter-agent communication have subsequently been proposed. These include ACL (*Agent Communication Languages* which details a set of so-called performative intentions of a message: affirmation, question, order, etc.), KQML (*Knowledge Query and Manipulation Language*, which is based on a protocol for exchanging information), or CNP (*Contract Net Protocol* for contractual networks).

In its efforts to promote the development of ABM, FIPA (the *Foundation for Intelligent Physical Agents*) sets the standards to foster the inter-operability of applications, services and IT equipment based on the agent paradigm (*Physical* means that agents can eventually be human). In 1999, FIPA defined a less-ambiguous ACL using a formal SL (semantic language) combined with a high-level communication protocol to remedy distribution problems, such as e-commerce. ACLs therefore define a normalised framework for interactions. They are mainly used by industry to ensure that a conversation is had and to facilitate inter-operability between heterogeneous systems.

However, Cormas users are not interested in this application domain. Up until now, they didn't try to have agents communicate between the various models implemented on different platforms. In most cases, models developed with Cormas do not use a predefined communication protocol and the *AgentComm-Msg-Channel* package (Figure 8) was only used for one or two models¹⁸.

By asking where the agents are, Drogoul, Vanbergue and Meurisse (2003) note that concepts of autonomy, pro-activeness and interaction, supposed to characterise agents are still at a metaphorical level, but are not expressed in computational properties". Regretting also this lack of autonomy, J. Ferber deplores the initial ideas that drove the pioneers of object concepts:

"The notion of the object in software engineering provided a whole range of concepts, technologies and methodologies. It transpired that in many cases, the initial needs of the objects, and in this particular case, the concept of autonomy, did not result in proper technological solutions. The object languages that we current have are only a pale reflection of the initial ideas that fixated pioneers in this field, notably Alan Kay with Smalltalk and Carl Hewitt with Plasma" (Ferber 2007).

Although A. Drogoul and his colleagues regret the lack of structural autonomy and proactive decision-making (goals-directed behaviour), they propose developing a dedicated methodological and semantic framework to operate proper agent-based models.

¹⁷ Techniques enabling computer programmes to exchange information have existed for several years, such as RPC (Remote Procedure Call, the oldest protocol for remote call procedures), RMI (Remote Method Invocation, a mechanism to allow an object to invoke methods on remote Java objects) and CORBA (Common Object Resource Broker Architecture, similar to RMI and available in numerous programming languages). However, these techniques only invoke remote methods and do not allow for monitoring full discussions.

¹⁸ The *PlotsRental* training model (described in note 11, page 20) is, in fact, the only one that I am aware of that uses the *AgentComm* package to visualise trade exchanges in a communication space (Figure 7).

The fact remains that autonomy is not a simple concept and living beings are less autonomous than they seem (see section **Erreur ! Source du renvoi introuvable. Erreur ! Source du renvoi introuvable.**). Their decisions are strongly dependent on their social environment, their physiological needs and their social coupling (Maturana and Varela 1994). Section 6 of my PhD thesis (Bommel 2009) addresses agent autonomy and I concluded by identifying two types of autonomy in ABM: one intended to *emulate* a living being's social autonomy and the level of independence and the other seeking to encapsulate an agent in protection systems that ensure their *computing integrity*.

Supporters of computing integrity reject the view of an action as a direct modification of the state of the environment and other agents. They want to separate the action from its consequences. This rejection must result in a new form of managing actions based, for example, on the "Influences and reaction" principle (Ferber and Müller 1996). For some, encapsulation which prevents modifying the attributes of an object is not enough. All direct references made to an agent must also be rejected. As a result, the object would only be visible by its interfaces that give its substance in social and physical spaces.

By extending this logic, the agent should be split in two. Its brain is tasked with cognition while its body becomes an environmental component amongst others, which no one has direct access to, not even its own brain. For F. Michel, this body-brain divide abides by the "constraints of environmental integrity":

An agent is not an entity able to calculate the consequences of its actions. As such, it is vital that an agent cannot directly alter the variables of the state of the environment. In other words, agents must not modify environmental variables. This is what we have called the environmental integrity constraint. (Michel 2004)

All these proposals to safeguard agent autonomy often require agents to be artificially split into two independent parts. They regard the agent's body as a foreign entity responding to the brain's influences. Ultimately, the environment has the final say on the action actually performed.

That said, must we use such devices to design any type of ABM? Do we really need a strong autonomy to specify a multi-agent model to support renewable resource management? Models developed using Cormas show that modellers chose not to use the *AgentComm* package which is nevertheless relatively simple to apply. Clearly, when we want to transfer autonomy from a living being to an agent, we have to take care to avoid certain artefacts. Indeed, there are many examples showing that directly modifying the state of an agent by another sometimes causes aberrations in behaviour, which affect the results of simulations.

Nevertheless, I don't think it is necessary to systematically use complicated model architecture to emulate this autonomy. I am therefore not in favour of these solutions which I find too complicated and constraining for the modeller. Based on their aims, the modeller can *emulate* the autonomy of their agents using a conventional approach (i.e. simply the object). It is, however, important to be aware of the possible biases that can result from direct modifications to variables. They must be anticipated and appropriate solutions must be proposed according to the situation. We therefore need to test how robust they are by checking the effects on agent behaviour and on simulations.

In terms of renewable resources modelling, I don't think the time is right to abandon conventional ABM approaches in favour of sophisticated and constraining tools to protect the agents' computing integrity. By contrast, modelling interactions must be addressed with due care.

4.5. Time and interaction management

Cormas does not insist on a pre-defined time management system but all the models developed with the platform use the "time step" simulation technique. While I demonstrated the effects of various time management policies in my PhD thesis¹⁹, we have opted to leave users the freedom to employ the time management system that suits them.

Unlike differential equation systems, multi-agent simulators use two types of implementation to manipulate discrete events. These are constant "time step" simulation, also called discrete-time simulation, and "discrete-event" simulation. The latter considers time as a continuous variable (real), however the system state changes discretely at specific times, i.e. events. The occurrences of these events are calculated at the start, or during, the simulation and are often dynamically ranked in a list called a scheduler. For these simulations, time, which is regarded as continuous, is represented by a series of discrete events, that appear at variable intervals. Using terminology proposed by Zeigler, Praehofer and Kim (2000), we subsequently call this the DEVS model (*Discrete Event System Specification*).

On the other hand, discrete-time simulations represent the passage of time by "discretising" time into regular "time steps", as with discrete dynamic systems. For these types of models, Δt is a constant (we generally consider it to have an integer value of 1: 1 second, 1 day, 1 year, etc.). With changes in state occurring during the interval $] t, t + \Delta t]$, a system variable can change the state every Δt period, while the state is supposed to remain constant between the two. Furthermore, entities are supposed to evolve simultaneously and all at the same time.

According to the Zeigler classification, these models belong to the DTSS (*Discrete Time System Specification*) model family. Simulations can be regarded as a DEVS discrete-event sub-type simulation where the ticks constitute events. However, their implementation is different and much easier to undertake. The models provide two entity activation procedures which are referred to as synchronous and asynchronous.

The *synchronous* approach, used mainly for cellular automata, considers that entities all evolve simultaneously (in parallel). A computer mechanism called double-buffering is commonly used to emulate a synchronous evolution in a network of automata. This consists of a two-stage update of the cell state. As such, the sequential activation order of each cell has no influence of the simulation results.

¹⁹ The technical part of my PhD thesis (Bommel 2009, part two) deals with time management related aspects (section 5), the concept of agent autonomy (section 6) and direct and indirect interactions (section 7).

In the *asynchronous approach*, from a *real-time* perspective, agents are meant to evolve simultaneously. All agents must have been activated only once at each step (n-asynchronous activation). In most cases, ABM uses this principle as implementation is simple and easy. That said, all the agents must be sequentially activated, one by one, at each iteration. Despite appearances due to the speed of operation, they do not evolve in parallel. In addition, each agent directly updates their visible state when they are activated. As such, at any given moment during a step, some agents have already changed state while others have not yet been activated.

This conventional form of time management can have significant effects on simulation results. When using common resources, for example, the first activated agent quickly takes advantage over the others. It always has first pick. The most commonly-used technique to resolve this problem is to randomly mix the activation order of agents at each step. Statistically, we subsequently restore a division by not systematically giving the advantage to the same agents. In keeping with *Sugarscape*, a great many models use this “time step” management process with random mixing.

While in some cases, this strategy barely influences simulation results, the consequences can be quite marked for others. You just have to imagine the effects of this management system on a forest-fire cellular automata (CA)²⁰. With synchronous management, we obtain, as expected, regular step-by-step outbreaks of fire, but if we use asynchronous management with a random mix of forest cells and an immediate application of the transition function, statistically we see that the fire spreads very quickly. The problem, in this case, is that the result largely depends on a random factor that is not intrinsically defined in the conceptual model. Although CA synchronous management is frequently very complicated to implement on agents, the modeller must find ways to manage agent activation that curbs this type of bias.

However, we can minimise the effects of discrete-time management. Many models use this random synchronous activation system without their results being linked to a random scheduler. Also, while the modeller decides on and justifies the agent activation order, variations in the results are regarded as being linked to the subject area: agent sorting by velocity, strength or proximity, etc. In this case, sequential management constitutes precisely an element of the model. However, many times, the ABM designer is unaware of the potential effects of this scheduling on the results of his simulations. The conclusions on his object of study can turn out to be an artefact. When discrete-time management is used, special attention must be given to agent scheduling and time granularity. This aspect is frequently the source of errors when replicating models²¹.

²⁰ The transition function is rudimentary: if a cell is in a “forest” state and at least one of its neighbours is on “fire”, it then switches to on “fire” in turn.

²¹ When they independently replicated *Sugarscape*, Lawson and Park (2000) and Michel (2004) concentrated on the effect of different time management systems (events or time steps). They sought to understand the reasons for powerful fluctuations in communities in the “time step” version but their conclusions differed. Lawson and Park consider that discrete event management should take precedence as it compensates for fluctuations. Michel rejects these conclusions and explains the

Regardless of paradigm used (differential equations, discrete System Dynamic, ABM with discrete-event or time-step simulation), modelling time is still a delicate aspect of simulations. At our level, time appears to pass continuously, even if seasons occur at regular intervals. To address continuous physical problems, such as movements and collisions of balls, some prefer to use mathematical, differential equation-type tools, while others opt for discrete-event multi-agent systems. These techniques are essential to analyse these types of problems, but they are challenging to implement, and errors can easily occur.

Many people think that multiprocessor architectures would resolve these problems. This applies to the authors of *Sugarscape*, who regret their current inability to use a machine based on a massive parallel processor network. In their opinion, it would enable them to run the simulation fully in parallel. These architectural layouts are possible for independent actions, but as soon as there are interactions, synchronisation is required. The same problems spring up again with conventional situations when using a common resource and therefore conflict resolution.

Despite appearances, these difficulties do not just constitute a technical obstacle. They mustn't force us to systematically use a given interaction model, like the "Influences-Reaction" type (Ferber and Müller 1996). Furthermore, is the fact that agents act sequentially and non-simultaneously, really a problem for all models? For models analysing resource access and use, running simultaneous actions is not necessarily the overriding rule. You don't necessarily have to apply a sophisticated interaction process, as is used for the collisions of snooker balls or to resolve conflicts when opening a swing door! This type of technique is not essential for resource management as the systems studied are primarily derived from discrete phenomena that don't necessarily require continuous processing. Furthermore, the "Influences-Reaction" management process, as supported by Michel, Gouaich and Ferber (2003) is not a neutral model as it designs the use of a resource that is equally distributed between agents. However, this choice should not be decided by computer techniques but must be regarded as an explicit decision taken by the modeller.

The way of managing time for indirect interactions (e.g. agent-resource) affects the model results, although it is unlikely that the effects will be less significant compared to direct interactions. Even if they are intended to represent a sector, trade interactions or any type of chain reaction, the modeller must take great care in the way in which he manages time and agent interactions. Often it is best to use a superior entity (a market or an official) to regulate these exchanges (see note 11, page 19).

Technically, no single time and interaction management system is better than another. The modellers simply have to realise that the system they have chosen belongs to the model domain. Their choices must be clear, explicit and justified. This is why Cormas does not force a choice in agent activation methods.

reason for these oscillatory phenomena is due to homogenous initial conditions coupled with the system's spatial constraints. He concluded that the DTSS method exacerbates simulation bias while the discrete-event method gradually eliminates them when the agents are activated asynchronously.

4.6. From model to game and from game to model

By seeking to gradually incorporate the knowledge generated by researchers and various local stakeholders, the ComMod process promotes consideration about how this local area develops. The aim of this specific foresight process is to collectively assess alternative paths of development. Starting from designing a shared vision of the current situation and what is most likely to happen (the status quo scenario), the aim is to assess the probable effects of other alternatives in terms of natural resource use (agriculture, fishing, mining and animal activity) and the organisation of producers or local public policies.

The overall approach is considered to be an iterative process based on a land→modelling→simulation→land cycle (Étienne 2010). This doesn't necessarily mean a growing complexity of a model that should incorporate more and more elements to better reflect reality, but rather accepting a range of models that subsequently form a real knowledge base.

Historically, the use of role-play appears early in the ComMod process. Already, in his thesis on the viability of irrigated perimeters in the Podor region of Senegal, Olivier Barreateau designed and implemented an ABM. However, to present his model to local stakeholders in Podor and get them to discuss water management, Olivier produced a simplified version of his model in the form of a role-playing game (RpG). This living version took stakeholders away from the computer-based model by giving the stakeholders parts to play. The model assumptions, forms interaction between agents and their behaviour could be discussed at debriefing sessions (Barreateau, Bousquet and Attonaty 2001). The ABM and RpG tandem can therefore be seen as the opportunity to open the black box of an multi-agent model and gain a kind of “social validation” from it (Barreateau and Bousquet 1999).

For a project that analysed the decentralisation of land-use plans in the Senegal delta, P. D'Aquino and his colleagues (D'Aquino et al. 2003) ushered in a type of inverse combination. Role-play games were firstly designed and run in the villages they worked with, involving the delta's stakeholders. Using the data from these games, the team developed ABMs with Cormas in which agent behaviour depended on rules identified and discussed in the game debriefing sessions. The simulations were then run in the presence of those who took part in the RpG sessions. Understanding the direct link between the two tools was made easier by the similarity of the interface components, especially the spatial representation. What appeared on the screen was an accurate picture of the game board, while various symbols can also mimic the designs on cards used in the game. By playing the game, this type of combination enables the players to easily understand the conceptual model's structure and principles, by coming up with scenarios and testing them on the computer, in full awareness of the computer simulation model's status. The model doesn't appear as a complex tool issuing recommendations, but just like a more effective role-play game to explore the various scenarios (Le Page, Abrami, et al. 2010).

The www.commod.org, managed by my colleague Christophe Le Page, features numerous case studies using the ComMod process, where the preferred tools are RpGs, without necessarily using a simulation model.

Apart from its many advantages (Janssen and Ostrom 2006), role-play can also be used to gather knowledge. Directly observing the behaviour of the players during a game session provides additional knowledge. The actions performed by the participants in the game, as well as their reactions following a given situation, must be observed in different ways. The players are subsequently asked during individual or group debriefing sessions to explain *why* they decided to take a particular decision in the game. By asking them about the information they needed to make these choices, they are encouraged to undertake an introspective analysis and thus succeed in formulating implicit knowledge.

Furthermore, the game separates players from reality and helps them to speak more freely, while strained social relations that are rarely discussed in interviews can be brought to light.

4.7. Hybrid-agent simulation models

Starting with the model domain, the delivery model can represent stakeholders in two distinct ways: (i) either by virtual agents undertaking pre-defined activities in a computerised ABM, or (ii) human stakeholders playing their role in a role-play game (RpG). Even though it doesn't fit the traditional sense of the term, an RpG can be seen as a representation of the world, i.e. a model. Indeed, O. Barreteau (2003) highlights the similarity between an ABM and a RpG: agent \leftrightarrow player, game-turn \leftrightarrow time-step, game board \leftrightarrow spatial, simulation \leftrightarrow game session. In this sense, an RpG can be regarded as a human ABM.

Two forms of simulation are possible using the same conceptual model: either a computer simulation by running this model in a simulator²², or by playing a role-play game in which the participants make decisions and interact within rules set by the conceptual model.

There are many intermediate situations between these two extremes, where specific decisions are selected by humans while others are automatically made by the computer. The term, "hybrid-simulation model" covers all these intermediate situations. The following table illustrates the range of situations:

²² According to Zeigler, a simulator is a full software application that can be booted and run on a machine (Zeigler introduced this concept in the second edition of his book (Zeigler, Praehofer and Kim 2000))

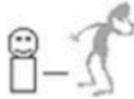
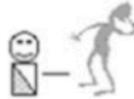
Nature of the decision	100 % human		Intermediate	100 % computerized
Typology of computational agents	Human agent = player	Simple composite agent	Hybrid composite agent	Computerized agent = virtual agent
				
	No avatar	Non-decision-making avatar	Partial decision-making avatar	Autonomous avatar



Figure 9: Agent types based on a split between human decisions and computer-specified decisions (Le Page, Abrami, et al. 2014). Illustrations from three uses of the same conceptual model (*FuturaAgua Project*, Costa Rica), with a game board (photo left), a conventional simulation (photo right, with producers) and an interactive simulation (photo centre, with pupils from the school in Guanacaste).

In chapter 3 (Le Page, Abrami, et al. 2014) of the book on ComMod (Étienne 2014), we present a classification of multi-agent/multi-stakeholder systems. On one hand, simulations involving human agents (RpG) are referred to as *HAM* (human agent-based model) while on the other hand, simulators based on computerised or virtual agents are called *VAM* (virtual agent-based model). Between these two extremes, we use the term, *HyAM* to refer to hybrid agent-based simulations that name participants in the computer system. An avatar, the computerised representation of a human agent²³, has no decisional autonomy. They are subsequently defined as a “simple composite agent”, or virtual pawn that the player uses. However, if an avatar acts potentially without the involvement of a player (for example, when it automatically carries out routine activities leaving strategic choices to be made by its player), it is considered to be a semi-autonomous entity, called a “hybrid composite agent”.

For all these intermediate situations, the computerised system is just a component of the simulation model (one of the parts of the game) and not a computer model in its own right. Moreover, among all the models developed with ComMod, several simulation models (in a broad sense) can be frequently used based on a single conceptual framework (model domain).

²³ The term *avatar* is commonly used to identify sets of information or digital characters that represent the residents of virtual worlds. Taken from Sanskrit, the origin of avatar comes from the avatars (*avatara*) of Vishnou who “descend from the sky” (Georges 2012).

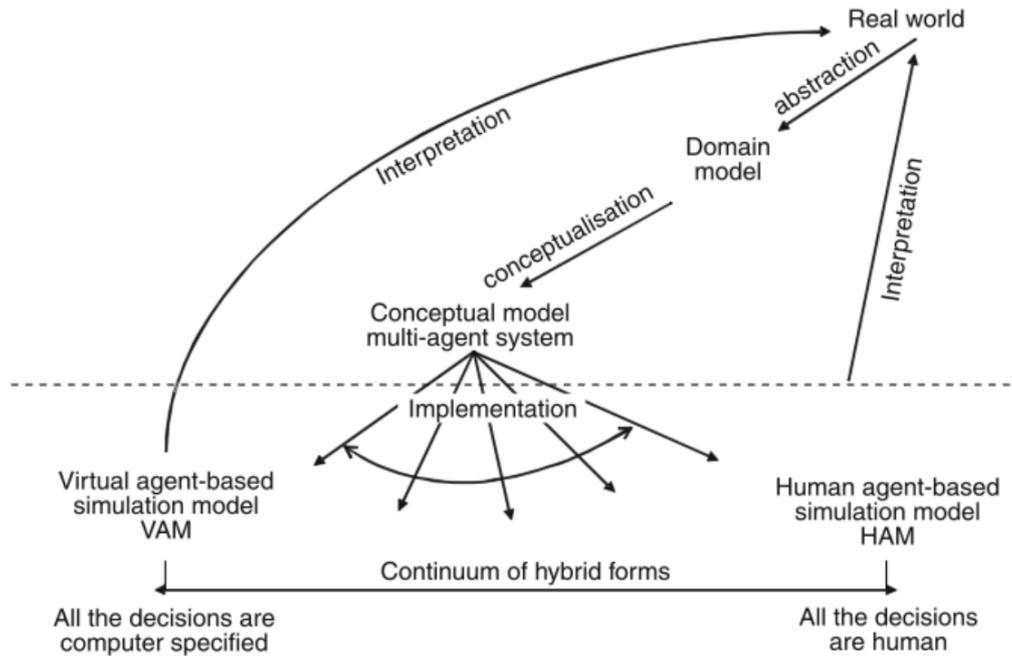


Figure 10: From real world to the implementation of agent-based simulation models (Le Page, Abrami, et al. 2010).

Using computer technology makes simulations rapid and calculations efficient. Five key functions can be highlighted: 1) rapid simulation of the resource process and the option to simulate the system in the long-term, 2) calculating and displaying social, economic and environmental indicators, 3) the visualisation of a space (the state of resources, agent positioning, realisation of activities, vegetation cover mosaic, river systems), 4) inputting and recording decisions made by participants and 5) recording games to replay them during debriefing sessions. The computerised version of the role-play game can repeat several sessions and occasionally in the presence of a large number of participants.

By contrast, an RpG session is much slower but aside from the entertainment it brings, it gives players more freedom in their actions and allows direct and non-verbal communication between the players.

P. Guyot defines participatory multi-agent simulations as “experiments undertaken in laboratories or on the internet, with human participants as part of a multi-agent approach” (Guyot 2006). He then explains that “each participant is sat at a work station and all interactions, designed as interactions between agents happen on the computer”. P. Guyot considers this type of simulation to be the “ideal multi-agent system”, yet most of the experiments that we conduct do not meet this definition which is too computer focused.

(Crookall et al. 1986) propose a classification of hybrid simulations based on the relative place of the computer and the control operated by the participants. For example, they call conventional simulations “Computer-Dependent” when the participants can only observe the simulation being run but not intervene. By contrast, “Computer-Based simulation” is similar to “first-person shooter” games (FPS) where a player continuously interacts with the

simulation. Dexterity and accuracy are what it takes to win. Between the two, “Computer-Controlled simulations” are regularly halted to give time to reflect and discuss between players. Finally, in the “Computer-Assisted” option, players do not interact with the simulation and one session is run away from the computer which only records inputs from the facilitators.

The interactive simulations that we use are broadly Computer-Controlled or Computer-Assisted simulations. It is important that participants interact with each other and with the simulator, but their ability to interact with the computer must not advantage specific individuals. The participants are key to the process in our workshops while the computer is just a support to assist the simulation by making the calculations easier. Unlike the distance that internet allows for, we favour physical proximity as the game has to reveal interactions between players, either through direct dialogue or non-verbal communication. It is often in these situations that we see how people behave, with moments of stress or arguments that shed light on a situation. Furthermore, projecting a simulated landscape on a horizontal surface brings people together. The participants gather around the lit display and place their avatars and carry out their activities. But, most of all, they discuss around this game board, they exchange objects and relive situations which they have sometimes experienced.



Figure 11: a game board and simulation projected on a horizontal surface that draws people together and creates a good mood (Clim-Fabiam Project, Piraquara, Amazonia).

In some cases, though not systematically, RpG or hybrid simulations provide information for the modeller, who can then spot cases of archetypal behaviour to feed into virtual agent-based model, or a “Computer-Dependent” simulation. In short, this is a conventional simulation that can be analysed more thoroughly.

5. Evolutions of the Cormas platform

5.1. Developments focused hybrid model design and use

As well as managing the Cormas platform and website, my colleagues and I (mainly Christophe, François, Nicolas and Bruno)²⁴ also train a small team to develop Cormas. The developments do not correspond to a well-defined set of specifications nor to good software engineering practice. There is no systematic quality control procedure to meet ‘customer expectations’, nor guidelines to “rationalise production and monitoring costs”. Until recently, upgrades to Cormas were done on an ‘artisanal’ basis, with additions or improvements of various kinds based on a need (often urgent) arising during a project or a training course. As we were all busy with development projects in the field, there was no one with sole responsibility for this task, which advances according to each team member’s availability. An IT developer would be very welcome! For example, we only just recently acquired a *versioning* system (GitHub) to transfer Cormas to Pharo (see section 8.2, page 71).

Despite a rather ‘hand-made’ approach and a lack of staffing in IT, Cormas has managed to form a community of practitioners in participatory modelling (Le Page, Becu, et al. 2010). The modelling training courses that we run on a regular basis (see section 7) play an important part in this relative success. Clearly, the platform doesn’t have the firepower of Netlogo, Repast or Gama, but it has found a niche in the collective modelling field and interactive simulation.

Our literature review from 2012 already showed a rise in the use of this type of models (*Game models*) to the detriment of their stylised theoretical counterparts:

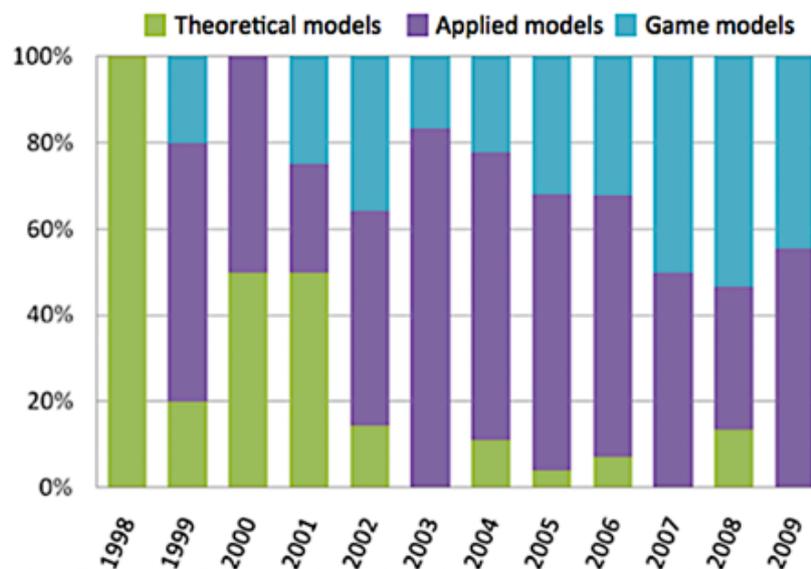


Figure 12: Developments in literature featuring models developed using Cormas

²⁴ The list of contributors includes, in lecturing order: Innocent Bakam, Hubert Proton, François Bousquet, Christophe Le Page, Pierre Bommel, Alassane Bah, Nicolas Bécu, Emmanuel Lieurain, Jean-Christophe Soulié, Paul Guyot, Jean François Lefevre and Bruno Bonté, with an impressive “gender issue” balance to resolve!

The number of theoretical models (in green) developed with Cormas began to fall in year 4. After that, the models were mainly applied to real-case studies (in purple). However, the most notable trend is the constant rise in the use of Cormas to assist role-play games (in blue), a feature that has been present since the platform's very beginnings. Today, the hybrid model category (*HyAM*, combining RpG and ABM) accounts for the majority of literature referring to the use of Cormas.

As a result, studies recently conducted on Cormas comply with this approach. Instead of watching a simulation without being able to intervene in the ongoing process, new tools now enable interactions with the simulator. Users can set their own indicators and choose to observe the simulation through filters. Given the preponderance of spatialised resources, users can also opt to observe part of the space (generally the part that involves them). They can also directly interact with the agent meant to represent them (their avatar) by moving them around or by sending them a series of messages and acting on the vegetation cover or rivers system using their avatar.

With this in mind, we are developing Cormas on two levels: 1) to facilitate ABM collective design and implementation and 2) to develop interactive simulations enabling users to play an active part in running a scenario on their own or with others.

In terms of a generic framework, Cormas enables users to specialise and refine pre-defined entities for their own models. The current version is especially suited to:

- Displaying specific points of view of a simulated landscape, opening several zoom-in options and specifying the “habitus” in order to see and interact with the simulation,
- Modifying the parameters of one or more agents,
- Manipulating an agent directly using a computer mouse by moving it to a specific spot, sending it pre-defined messages or even designing new forms of behaviour with the activity diagram editor, which are then directly enacted by the agent.
- Time travel in a simulation and re-simulate from a previous state (bifurcations), or simply replay a previously stored simulation,
- Distributing a simulation to several machines to monitor its evolution and manipulate entities remotely.

5.2. Model design guidance

As Cormas is intended for non-computer specialists who must familiarise themselves with object design and programming, the platform offers a certain number of interfaces to help them develop their models.

Ever since I joined the team, the training sessions that we provide focus on the design and formalisation aspects of models rather than on programming. Courses entitled, “Introduction to Object concepts and UML” (statistical and process-based aspects) are combined with numerous exercises after which participants start to become competent in object modelling. They subsequently apply these skills to design a simple model in a group by proposing

various UML diagrams. They must then translate these diagrams into code to implement their first simulator.

If we look at training course evaluation feedback from participants, learners especially seem to like formalising models using UML. They understand the benefits of mastering this formalism, both to publish their model but primarily for the individual or group design stage.

We have developed a UML class diagram editor that can be used to design the structure of a model and generate source code (Uhnak and Bommel 2016). Conversely, this editor can also read existing code to generate a diagram by retro-engineering.

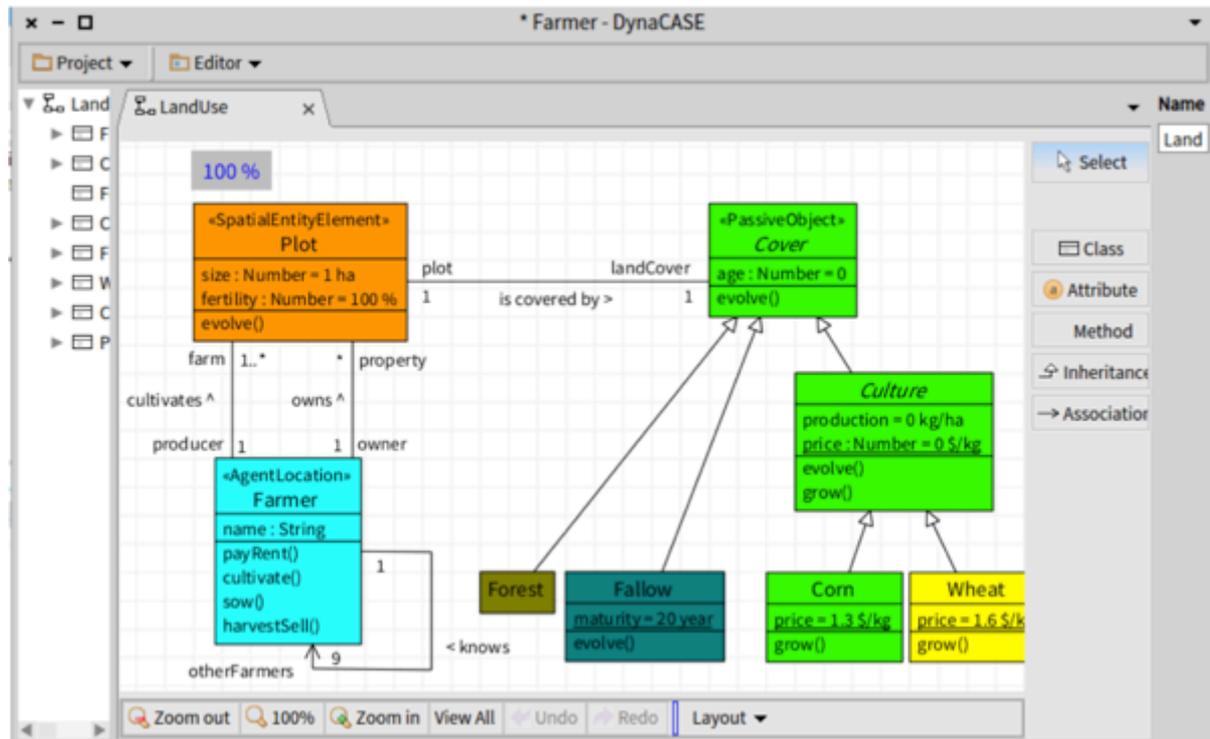


Figure 13: Full view of the UML editor featuring a simple “land-use” model (ibid.)

Obviously, the code generated cannot run a simulation, it only contains the model structure with classes, attributes (with their default values) and associations. Methods to instantiate a simulation, activate agents and perform their behaviours must still be programmed. That said, the framework’s generic classes can be re-used by specific agents of an ABM. As Cormas is geared to collective model design, the code generator makes it considerably easier for participants to intervene and develop models on their own social and environmental systems.

Unfortunately, this editor is not yet entirely integrated into the official version of Cormas but comes in the form of a separate software application (a specialisation of *OpenPonk*, Uhnák and Pergl, 2016) able to generate XMI files and Smalltalk code for Cormas. It will be fully part of Cormas when Cormas-Pharo will be officially launched (see section 8.2)

Pending this development, modellers can use a range of tools to implement their models and as they use a framework, they must specialise in specific predefined classes, mainly “social”, “spatial” or “passive” entities.

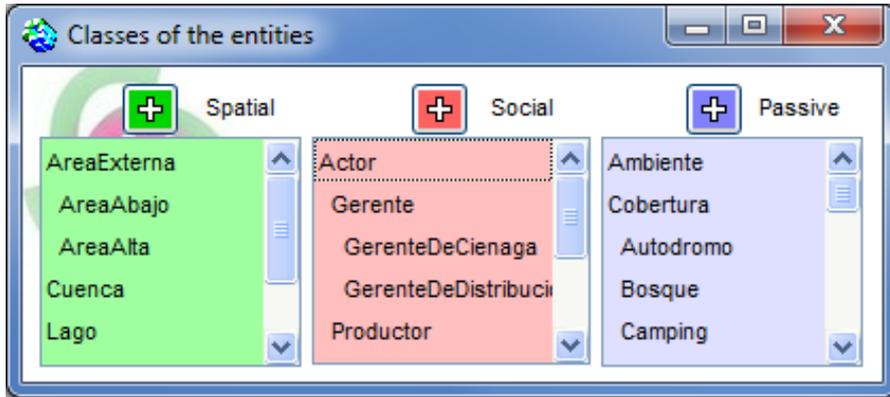


Figure 14: Class management

Attributes can be added when defining a class and Cormas helps the modeller to set the initial value of these attributes. To test the effect of a new value, a table featuring all the model parameters can be used to temporarily modify the values. For example, it is easy to change the initial number of “restrained ruminants” (ECEC) as indicated in the following screen capture.

The tools, in this case, also have an educational role as they enable the learner modeller to identify the parameters of their model from the code. Instead of losing these values in a sea of instructions, these key elements are clearly identified and easily accessible for future maintenance or transferring the model to other people.

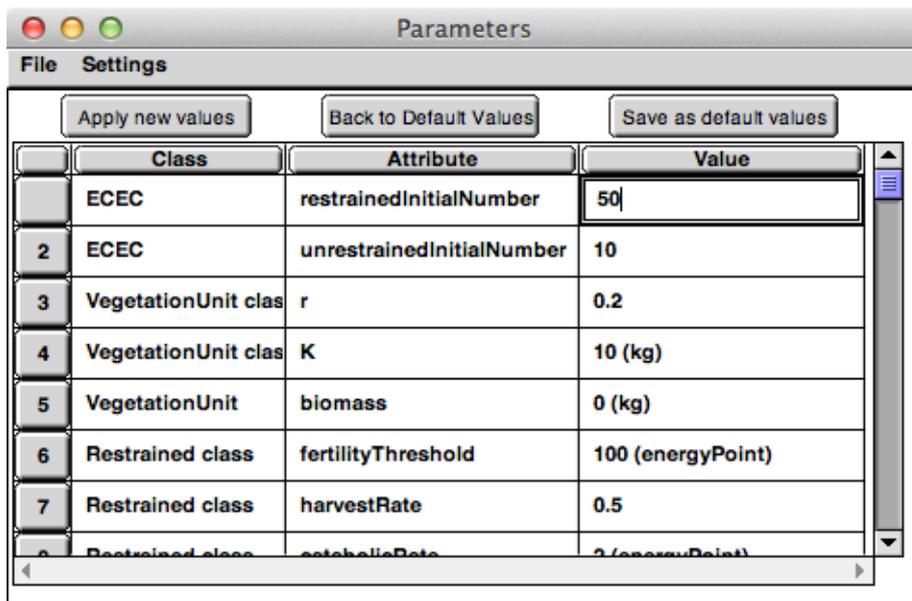


Figure 15: Parameter interface

Cormas also offers an additional UML tool called *Visual Inspector*.

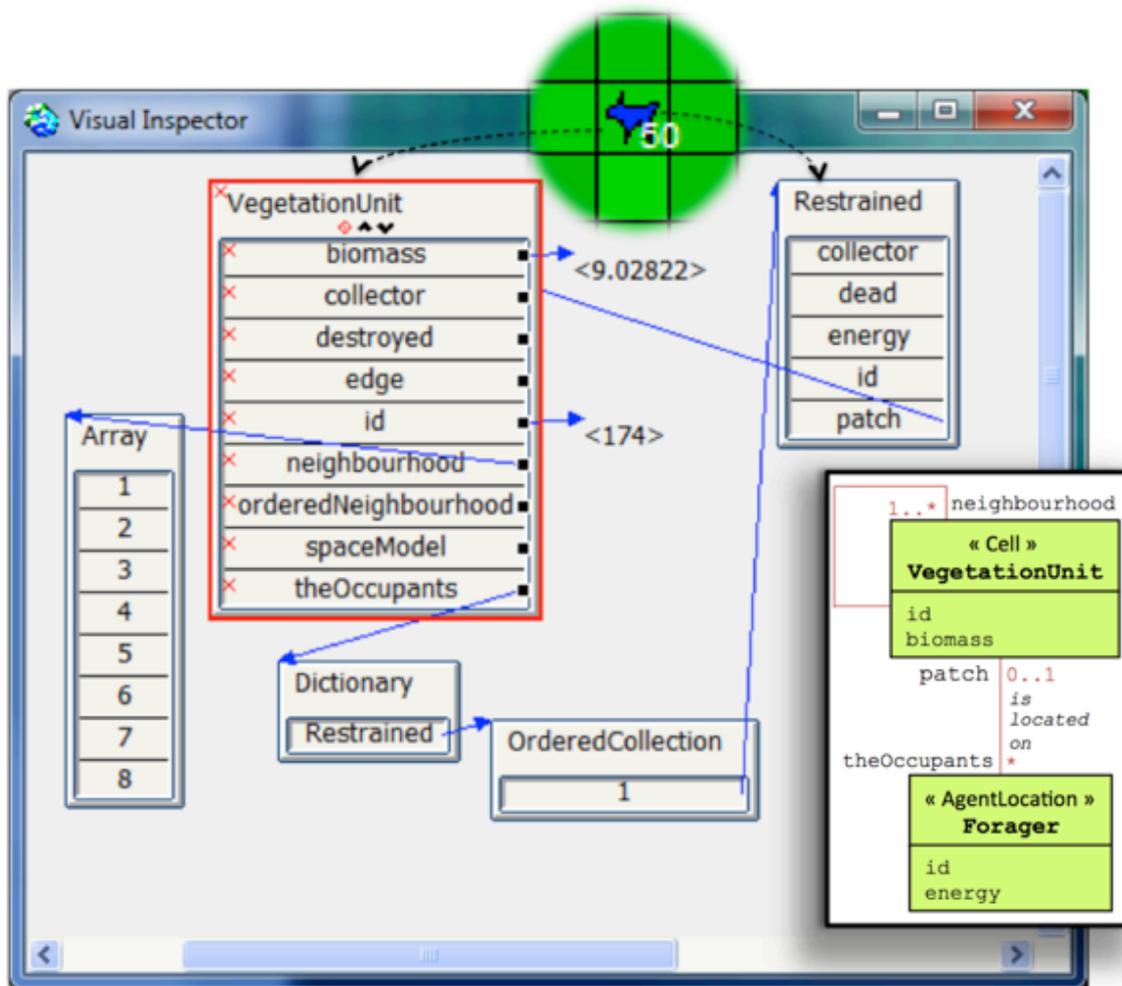


Figure 16: The *Visual Inspector* displays the objects and links to explain the development of a class diagram (white box)

This is an “object diagram” editor that makes it possible to visualise an agent in a simulation, then by clicking on each attribute to display its value (name, age, ID, etc.), as well as links that connect it to other entities. As such, you can navigate from object to object by gradually revealing the network of links that connect them. For instance, a cell is connected to its 8 neighbouring cells and can access their occupants, each one of them knowing, in turn, the cell in which they find themselves.

This tool is therefore practical in the learning stage to illustrate the concept of associations between classes and that of links between objects.

5.3. Points of view and multi-windows

“We don’t want to model the ecosystem,
but the ecosystem seen from several points of view” (Bousquet, Antona and Weber 1994)

From the outset of *Cormas*, the focus is on the points of view concept, as the quotation above emphasises. The aim is to follow a simulation according to various aspects (physical space, communication space and indicators). It was therefore important to observe the spatial table

according to several Points of View (PoV), such as viewing a landscape from a property perspective or based on vegetation cover.

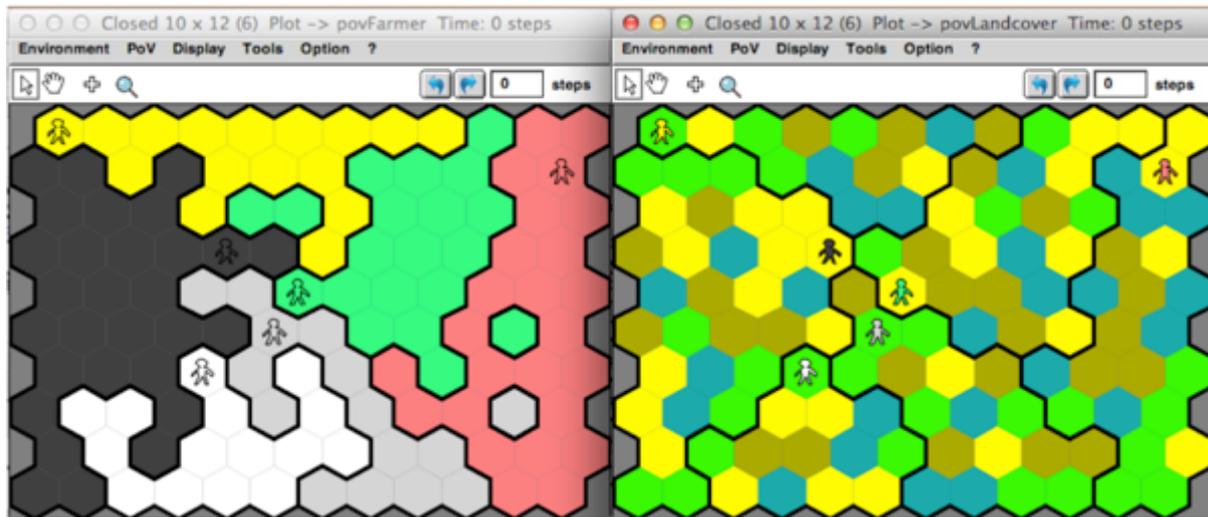


Figure 17: Two points of view of the spatial grid showing 6 farmers and their land ownership (left), and the same agents on their operating farm (right). In this example, vegetation cover is displayed. After leasing out fields to each other, the agents' land ownership (left) is different to the farms they actually operated (right).

Figure 17 shows two distinct points of view: *povFarmer* displays the fields colour-coded to their owner, whereas *povLandcover* shows the distribution of different land cover in the area. You can visualise the spatial environment through several windows at the same time²⁵. As the model is independent from the chosen option to observe it, different PoVs can be selected to display (or mask) entities.

The system's default setting provides 3 PoVs for each class: "nil" which masks the instances of the class, "default PoV", which allocates a standard figure (or colour), and "povId", which displays each entity in a different colour. It is, nevertheless, easy to identify other PoV using the *PoVSetter* interface.

Figure 17 also features the aggregation delineation, i.e. land ownership properties on one side (left) and farms actually operated by agents (right). Composed of plots (*SpatialEntityElement* or other aggregates), these hierarchical spatial entities are dynamically composed (or decomposed, merged or split) and enable specifying dynamics at different levels (e.g. scrub encroachment on grazing land at cell level, or the growth of a forest on its boundary, at aggregate level).

²⁵ Initially, simultaneous display was not available and I had to reconfigure part of the Cormas core system so that the platform was more in tune with MVC architecture. The new spatial grid uses the *HotDraw* editor, originally designed by Kent Beck and Ward Cunningham, then re-implemented in Smalltalk by Patrick McClaughry, followed by (Brant and Johnson 1994). The *HotDraw* framework also complies with MVC architecture. As such, an agent is the model for several *EntityPOV* which play a role in the model for figures that are eventually displayed on the grid.

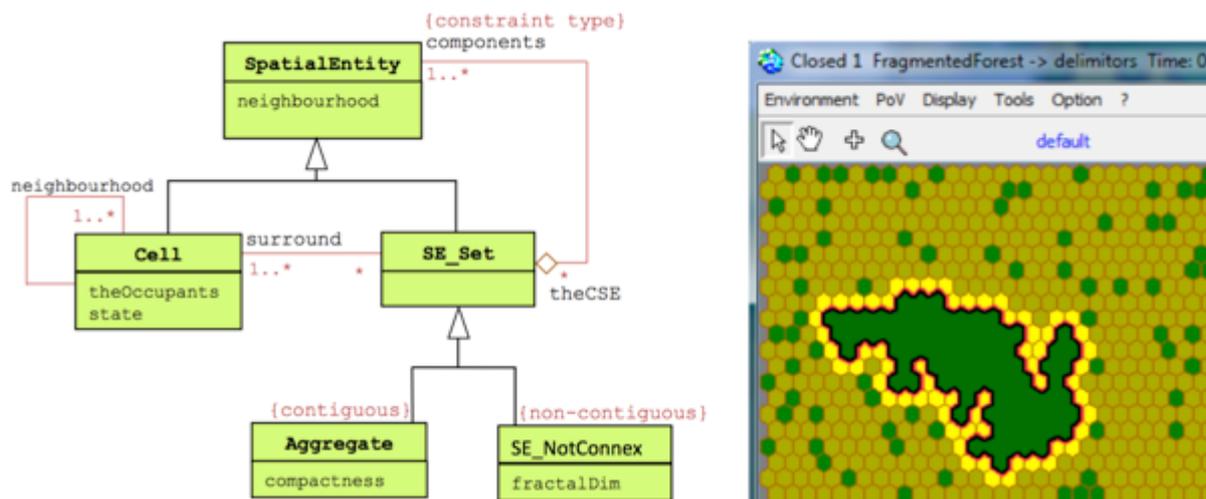


Figure 18: Left: class diagram featuring the hierarchical organisation of spatial entities. Right: spatial grid with plots (and their own dynamics) and a grove of trees growing on its boundary (yellow).

S. Lardon (Lardon et al. 1998, Bommel et al. 2000, Lardon et al. 2000) began this work on hierarchical spatial entities which was subsequently added to Cormas (Le Page et al. 1999).

To display only part of the space, it is possible to open a new window by zooming in on a part of the grid. In hybrid simulations, it may be interesting for the players to have access only to a limited view of the space, in order to work on information asymmetry problems.

A configuration interface developed by N. Bécu re-uses Cormas' basic concepts (PoV, manipulation) to customise the spatial grid by specifying the available points of view and ways to interact with model entities. This capability is based on the *habitus* concept defined by Bourdieu as “the set of ways of being, thinking, acting and feeling that belong to an individual” (Bourdieu 1980). According to Bourdieu, a habitus structures an individual's behaviour and actions. As such, when developing a hybrid ABM, Cormas' *Habitus* feature helps the modeller to restrict the various roles and perception of an agent-avatar, i.e. a player. Defining a habitus in Cormas, means defining (by means of a specific interface): (1) how the user can see the space interface, which entities are displayed and how, what information is available (text or agent-tracking), and (2), the way in which they can interact with the grid interface, which entities can be created and what actions can be undertaken (move about, consume, slash and burn, etc.). By altering these configuration parameters, the modeller can develop various ways to access information on the simulated system.

As such, two distinct configurations provide various points of view and result in asymmetrical information and actions between players. N. Bécu frequently used this capability to address suburban sprawl problems and its effects on loss of farm land and forest areas, as well as habitat destruction and fragmentation on biodiversity. To address these questions and foster a discussion on environmental conservation measures for municipalities, he developed a distributed hybrid model that simulates interactions between changing land-use and two iconic species of the French countryside, as well as groundwater quality which depends on the type of land-use. The players (Mayor, property developer, forest ranger, farmer and ecologist) have specific PoVs and actions.

Such asymmetry of visualization and action enables participants to assume the role of real stakeholders and to better understand their constraints, their points of view and the reasons for their choices, which are often misunderstood by others, which also often harm biodiversity (Becu, Frascaria-Lacoste and Latune 2014).

5.4. Interaction with simulation

To interact with a simulation, you can modify entity parameter values at any time (as discussed above) but you can also directly influence the space and agents during the simulation. There are two main ways of doing this: on all entities at the same time or on specific entities. In the first case, the user can change the state of a group of agents or create a new one. In the second case, the user can open the “Manipulation” interface to individually control an agent. Another way is to open a contextual menu on an agent and select a message from an automatically generated list (thanks to the *introspection* mechanism) containing all the methods belonging to the class and sub-classes for that agent.

The following screen capture shows two ways of sending messages to an agent. On the left, each *Unrestrained* agent performs the “step” method when the user clicks on it, while on the right, the user clicks on an agent by selecting a method from the drop-down list.

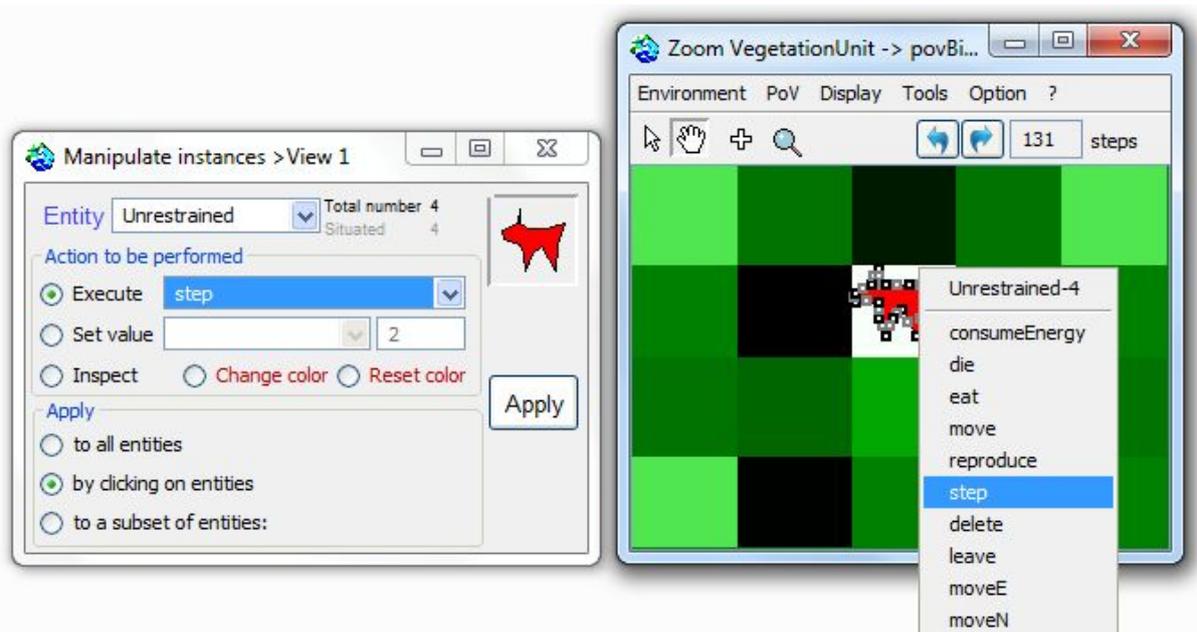


Figure 19: Two ways of sending an agent a “step” message. The Manipulation interface (left) enables an action to be performed or to change the value of attributes of one or more agents.

In addition to agent-avatar interactions for an interactive game, “this option also proves to be highly beneficial in the ABM verification stage. It would be useful to use it in model replication protocols” (Le Page 2017).

5.5. Exploring models

We only know something by acting upon it and by transforming it.

Jean Piaget, Psychologie et épistémologie, 1970

Contrary to popular belief, designing an ABM does not immediately result in understanding how it behaves. Indeed, time plays an active and decisive role by gradually activating the entities. The sequence of activities and interactions can generate some surprisingly and difficult-to-predict results. Although the elementary mechanisms are simple, we cannot account for numerous elements that influence each other (Deffuant et al. 2003). By setting the simulation in motion, this animation (from the Latin word, *animare* or “give life to”) gives the model a voice. The simulation then helps us understand how the ABM works and to assess if changes in the virtual system are consistent with the one it is meant to replicate.

However, a single simulation is not enough to understand your model. It has to be explored in-depth so that the final user of the model forms a model of the model, i.e. an understanding of the way it works separate from using it to run a specific experiment (Amblard, Bommel and Rouchier 2007). This exploration not only identifies and corrects the simulator’s anomalies but also provides the analyst with a better understanding of the model’s behaviour. Once completing this exploration, the user is able to identify the model’s behaviour classes from initial conditions or certain parameter values. This involves pinpointing which conditions and which parameter values correspond to the likely emergence of a particular type of behaviour. This analysis stage is unquestionably one of the most challenging steps but it is vital because if you can control your model, you can *explain* the reasons for each phenomenon generated by the simulation. This knowledge also helps to better anticipate the model’s reactions and to better explain the subsequent results, while providing some explanation to questions raised at the start of the process.

However, exploration is often neglected. Often, after the design stage then implementation, there is little time left to address this new stage in the modelling process. We often prefer to make the model even more complex to better “mirror reality”, rather than giving it a ‘thorough shake’ to understand all the consequences. Yet, as (Saltelli, Tarantola and Campolongo 2000) highlight, analysing sensitivity is a “vital part of modelling”.

Although most platforms have tools to visualise indicators, not all offer tools to easily explore a model. This does not simply equate to altering parameter values or re-running simulations, but also saving results in properly stored files (by limiting manipulation errors). Cormas provides a sensitivity analysis module for learner-modellers to easily produce experiment plans, without modifying the model’s code. Using dedicated interfaces, the modeller can launch sensitivity analyses in 3 formats: simple stochastic analyses that are repeated several times, OAT analyses (*One factor At a Time*) to study parameter hallmarks (gradually, or randomly, making changes to the value of a parameter in each simulation) and cross-referenced analyses where the values of several parameters are altered simultaneously. Data from these analyses (gathered in the form of time series, or min and max averages over a period of time) is saved in CSV or Excel formats. The data contains the conditions of each

simulation (parameter values analysed, random seed value, duration, etc.), while the results are processed with a suitable statistical software application, such as SAS or R (<http://www.r-project.org/>).

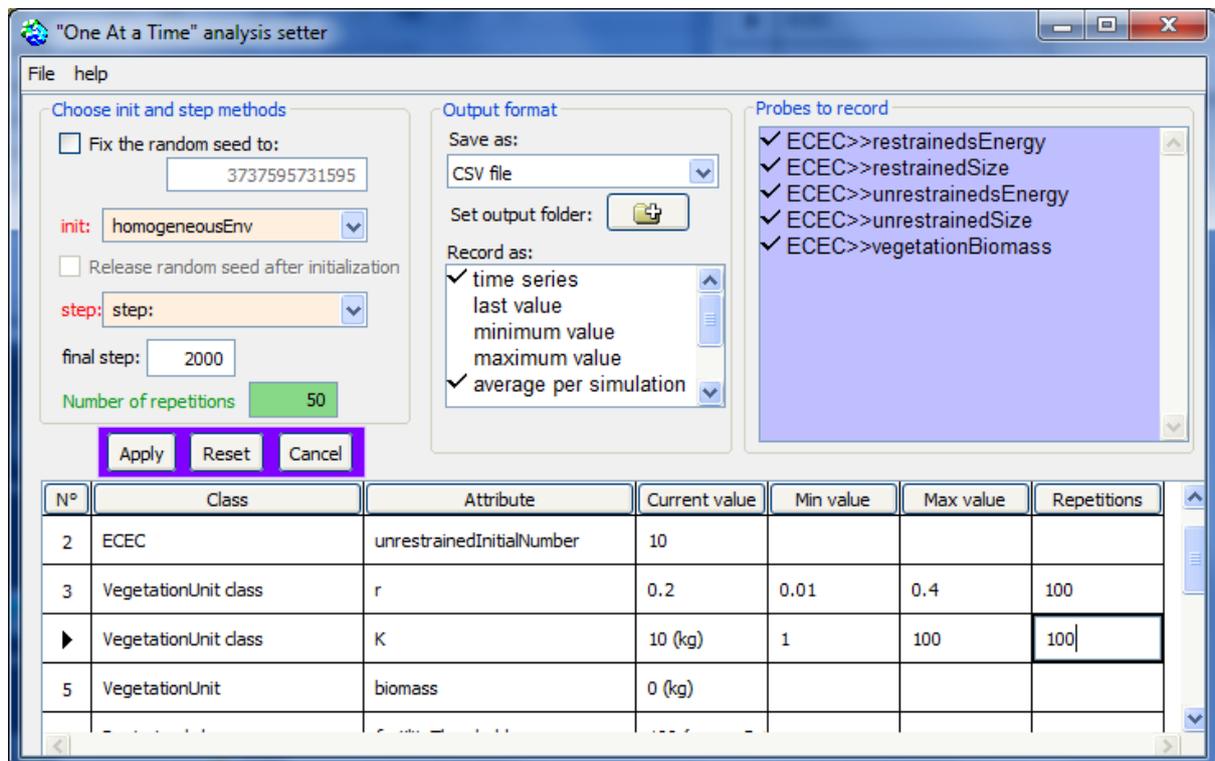


Figure 20: OAT sensitivity analysis interface to launch Monte-Carlo explorations.

Furthermore, B. Bonté coupled Cormas and R to control Cormas from R and design experiment plans directly in R. This will be the preferred approach for future versions of Cormas in Pharo.

Finally, my colleague, E. Delay, has developed a plug-in, Cormas-Pharo, in *OpenMOLE* (Open MOdeL Experiment: <https://openmole.org> and <https://github.com/openmole/cormas-plugin>) to explore and optimise ABMs by harnessing the power of the massive, parallel cluster or calculation grid-type calculation environment.

5.6. Distributed simulations

Thanks to the work of N. Bécu and J.F. Lefevre, a simulation can be distributed on several machines. This does not mean launching N simulations in parallel (we use *OpenMOLE* for that). In fact, distribution means several users can remotely view the same simulation (with different points of view) and can manipulate the entities in the simulated world.

The distribution architecture chosen does not comply with the IEEE standard for conventional video games as it applies more to real-time applications introduced by the

commercial and military gaming industry (massive multi-player games). Our aim is not, for example, to resolve complex dead-reckoning²⁶ problems for massive online simulations.

In Cormas, the distribution is based on Client-Server architecture. The model is not entirely duplicated on each computer, only its views and its controllers (according to MVC). As such, a single computer runs the simulation (the server) while the other connected computers (the clients) display specific points of view of the virtual environment and propose limited control over the simulation. The remote viewing capability means that several users can manipulate their agents and act as a group in the same virtual environment.

This architecture leaves no doubt concerning the state of the world perceived by each client. However, network traffic linked to the information displayed can quickly become too great if the simulation is run with a large number of entities. The architecture that I developed for my first thesis is more akin to current standards for video games and we have developed a robust, alternative peer-to-peer system, implemented on the MadKit platform (Michel, Bommel and Ferber 2002). This architecture by duplication (that I called *dupliqua*) was developed to overcome X-Window drawbacks by limiting the number of messages exchanged on the network. Similar systems are now widely used in the video-game sector. The idea is that each machine holds a complete copy of the simulation and just inputs from the users are exchanged so that the simulation maintains its consistency. For round-the-clock multi-player “first-person shooter”-type games (FPS), this architecture creates divergences between simulated worlds that need to be corrected (the famous dead-reckoning). For the interactive simulations that we organise (that are not continuous flow simulations), it is simple to ensure a simulation remains consistent. When we will switch to Pharo, we will re-use this type of distribution.

Although a simulation can be distributed on Internet, we prefer to use this capability on networked computers in the same place. We think that being close together is important. It brings greater depth and a more natural touch to interactions if there is face-to-face dialogue or non-verbal communication between participants.

5.7. Executable activity diagram

In Cormas, a UML editor is used to draft simple activity diagrams. For a simulation, these diagrams are performed directly by agents, without needing to be translated into code. They are interpreted on the “fly”. As such an agent’s behaviour pattern can be modified without having to code it. The simulator can also be modified while running, without stopping or re-starting the simulation.

For simplicity’s sake, the elements at the editor’s disposal are limited to initial and final nodes, decision points, simple activities (without input or output parameters) and transitions. One decision point authorises just two output transitions (true or false).

²⁶ To save bandwidth and avoid lag effects, dead-reckoning estimates an entity’s current position by using its previous position and calculating its new position based on known or estimated speeds over the course of its journey.

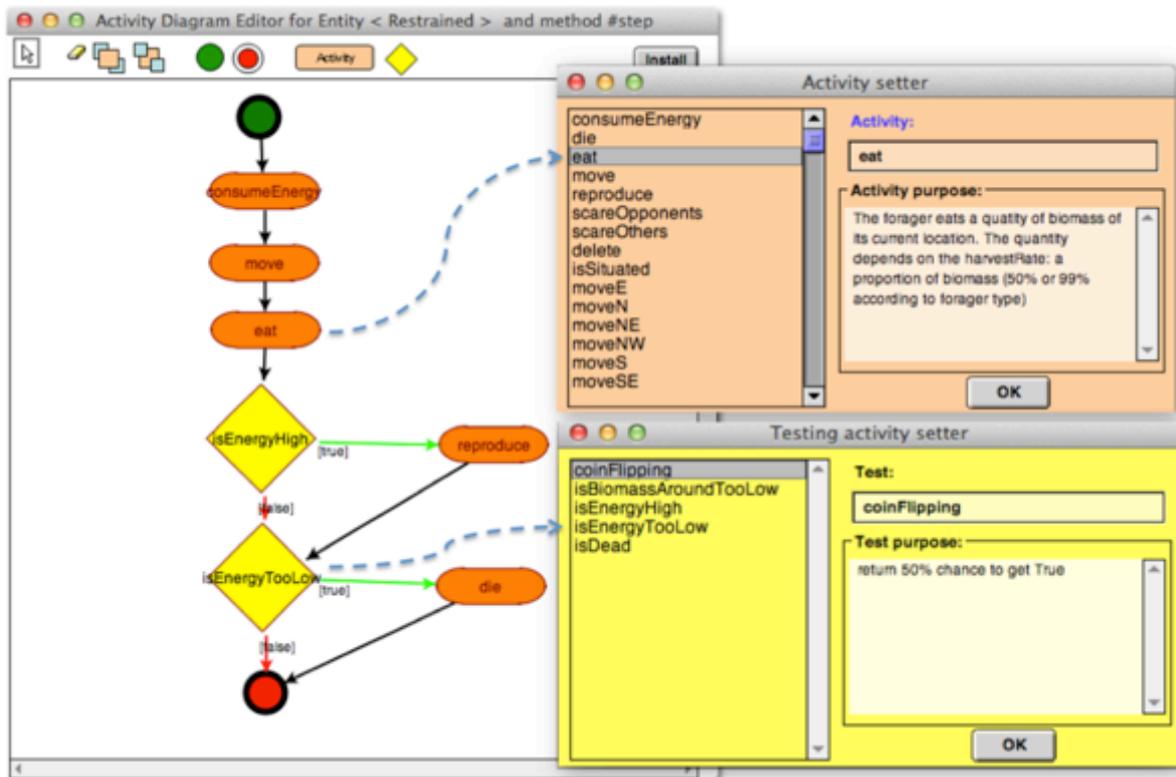


Figure 21: The activity diagram editor (left) and two activity selection interfaces (right). Each list of methods for selection is automatically generated by the introspection process. For decisions (in yellow), these lists are generated by inspecting only the *Testing* protocol methods.

By selecting an activity or a decision point from the tool bar, the user can add a new element to the diagram. Next, they choose the operation that this element will perform. The user makes their selection from an activity list automatically generated from available operations in the target class. The user can then draft a transition between two nodes. They must draft two transitions from one decision point, one where the decision test response is true (green) and one for when it is negative (red). As such, from these basic operations already defined by the modeller, anyone can generate new upper-level behaviour without any programming skills.

The editor does not dispense the modeller from programming his model. The aim is to collectively design an agent's behaviour by organising the sequence of activities by plug-and-play. These basic activities are methods (software bricks or components) that have already been coded by developers.

The editor is tailored to non-specialists, so it has been designed to be as simple as possible. This is why it does not contain sophisticated functions like Swimlanes, iterations or concurrent events specified by UML 2.5 (OMG 2017). Conversely, this simplicity enables anyone to play a more active role in modelling design with greater efficiency by immediately assessing any modification. We refined it and used it for the first time in the *SequiaBasalto* Project, with Uruguayan livestock farmers (Bommel et al. 2014).

The editor does not meet the "Executable UML" standard (xUML, Mellor and Balcer 2002, OMG 2008), whose specifications need a compiler to translate the diagram into code. In

Cormas, an activity diagram is not compiled in code but directly interpreted by the agents. In other words, each activity diagram is recorded in the model in the same way as the rest of the source code and can be re-opened at any time, modified and performed without compilation. By capitalising on the advantages of Smalltalk (reflexive language), the diagram that describes the behaviour of an agent can be modified while the simulation is being run. As soon as the activity diagram is recorded, the agent begins performing its new behaviour. This specific feature can be useful when a user observes the pattern of a simulation and wants to test how a change to the agent’s behaviour could change the course of the simulation.

5.8. Backward simulation for time travel

As with many other platforms, time moves on a time-step basis in Cormas (section 4.5), but you can step back in time in a simulation. As reverse-time calculation of activities is mathematically impossible, Cormas does not simulate stepping back in time. But instead, successive states of the system must be recorded to activate the step back function. As such, to step back to a previous state corresponding to time T ($T < T_{final}$) of a simulation, Cormas deletes the current state and simply restores the recorded state at T . You can therefore navigate in the simulation time, backwards or forwards by restoring the complete, previously recorded, states of the system.

The following figure shows the main Cormas interface with setting buttons for the simulation. When the user initialises a simulation (red button on left), they can choose to activate, or not, the “Enable stepping back” mode. The buttons with the red arrows are then used for standard simulations (without the step back option). If “Step back” was activated, the purple buttons can be used to go back or forwards in the time covered by a simulation.

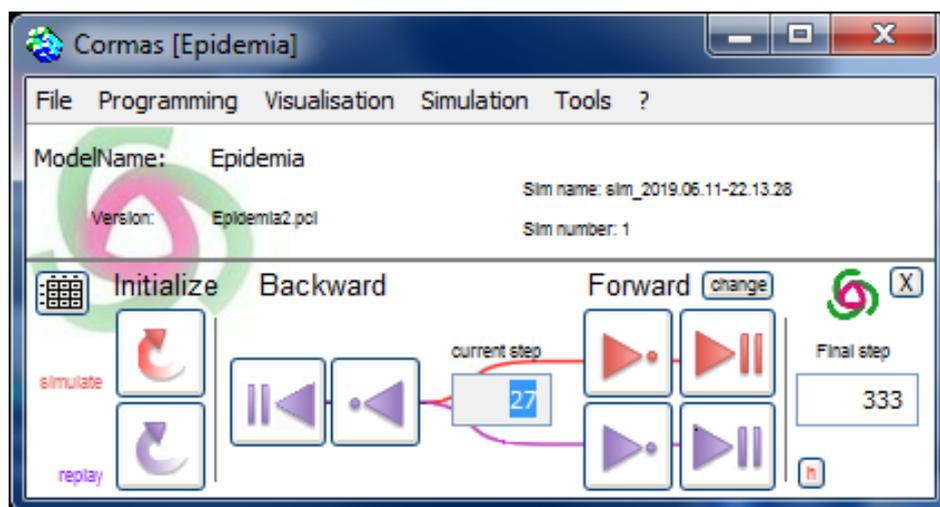


Figure 22: Cormas main interface with the “*Simulate*” (red) and “*Replay*” (purple) buttons.

In this example, the simulation has been run over 333 steps. The user has typed 27 in the “current step” box and Cormas has restored the system’s state at the end of step 27. Clicking on the “backward” will restore the previous state (26), while another click on the “forward” button will restore the time at step 27.

Travelling in time helps to analyse the model and check if its mechanisms are consistent. For example, by trying to understand a form of behaviour that the user finds strange, they can return to a specific moment, just before the anomaly began and, as with a film, restart this state and follow it slowly to see how the entities act in a specific way. However, starting from this specific state, the user can also run a new simulation (red buttons), step-by-step, to check if the entities are behaving similarly or if the system is evolving differently (this is called a bifurcation, see the following figure).

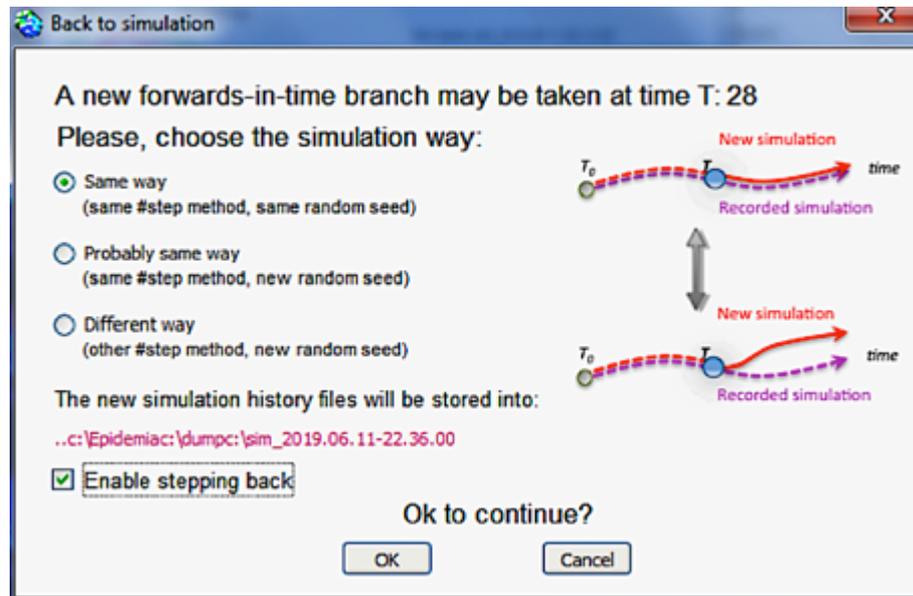


Figure 23: Bifurcation interface to restart a simulation (*simulate*) from a state recorded in the previous simulation (*replay*)

When restarting a simulation from a recorded state, Cormas gives 3 options: 1) simulate by retaking exactly the same way (in this case, the same random seed is used), 2) simulate by probably retaking a similar way but with a new random seed, therefore with different randomly calculated values, or 3) by changing scenario and selecting another step method of the Scheduler.

So, just like “Smoking / No Smoking” (the 1993 film by Alain Resnais, in which characters, all played by Sabine Azéma and Pierre Arditi, experience several versions of their lives based on the choices they make at key moments), Cormas charts out several scenarios from the same initial state, by stepping back in the simulation time and testing alternative decisions.

Furthermore, as initialising a simulation can create artefacts (all agents of the same age, for example) it is better to run a simulation up to a virtually balanced state. This state can be recorded, as a snapshot to become the starting point for future simulations.

Finally, this system state snapshot and restore capability is also used to manipulate agents: the “undo” and “redo” buttons in the spatial grid can be used to cancel or reactivate an action by the user. This is particularly useful for interactive simulation workshops.

6. Models developed with Cormas

Ever since I joined Cirad, I have helped design and implement some forty multi-agent models using Cormas. Most of them can be found on the Cormas website (<http://cormas.cirad.fr>) in French and English versions (and occasionally in Portuguese or Spanish). These projects have often resulted in me making modifications to the platform.

6.1. List of models developed

As explained in the introduction, the models developed cover a wide range of subject areas., as can be seen in the list shown in the following table (models developed with participants during training courses are not included).

Taking the classification system proposed by Le Page (2017), the table features the name of each model and the subject. In the “Lead contact” column, it should be noted that my involvement in the design of these models varied: given that by definition, participatory modelling involves several contributors, it is sometimes difficult to define any one lead person for a model. When I did most of the coding for a model, my name appears in the column. Otherwise, only the project manager’s name is shown. A red asterisk (*) has been added next to the lead contact’s name for those models having featured in a PhD thesis. The fifth column indicates published work (referenced in the CV) featuring this model. The first column, “Type” features the following coded symbols:

- ξ: replication of an existing model
- ♣: a computerised role-play game (HyAM)
- ℞: a realistic empirical model (that uses data observations)
- Ψ: a stylised model (or demo)

Table 1: List of models developed

	Type	Name	Subject	Lead contact	Papers
1	♣	AguaLoca	Water use and property processes on the outskirts of Sao Paulo	R. Ducrot	2004a; 2007d
2	Ψ	Alamo	Public farming and forestry policy and landscape change in the Grands Causses, in the Southern Massif Central	R. Lifran	2003c
3	℞	Amaz	Comparing different strategies of land use and their consequences in terms of Environmental Services in the Amazon	R. Pocard & P. Bommel	2008d, 2012n
4	Ψ	Aquifer Pollution	Water flows and contaminant spread in an aquifer	P. Bommel	

	Type	Name	Subject	Lead contact	Papers
5	Ψ	Arapey	Cattle farming production based on investment and rotation strategies	H. Morales *	2004b, 2005f, 2006c, 2010c
6	℔	AWARE	Water permit allocation in South Africa	S. Farolfi	2008b
7	Ψ	BrouteLaForêt	Spatial representations and individual, space and society interactions	JL. Bonefoy	2005c
8	℔	Burkina	Land quality indicators in Burkina Faso	S. Guilobez	
9	♣	Cienaga	Water volumes and quality at the Cienaga Dam, Jujuy, Argentina	G. Leclerc & P. Bommel	
10	♣ ℔	ContaMiCuenca	Water management game in Guanacaste, Costa Rica	G. Leclerc & P. Bommel	2015c, 2016b, 2016c, 2017j
11	Ψ	Demo Aggregates	Examples of spatial entities, aggregations and partitions of space	C. Le Page & P. Bommel	
12	Ψ	Demo Aquifer	Water flow in an aquifer	P. Bommel	
13	Ψ	Demo ArcsNodes	Spatialised networks	P. Bommel	
14	Ψ	Demo Diffuse	A simple model for the release of pheromones by ants	P. Bommel	
15	Ψ	Demo WayTo	The shortest path under duress	C. Le Page	
16	℔	Dinamica Parcelas	Land-use processes in the Argentinian Pampas	P. Arbeletche * & P. Bommel	2007f, 2008c
17	Ψ	Dps	The spatialised prisoner dilemma	F. Bousquet	
18	Ψ	Dricol	Developing agreements for common resources	B. Locatelli & O.Thébaud	
19	ξ Ψ	Ecec	Changes to cooperation in an ecological context. Replicating a theoretical model by Pepper and Smuts	C. Le Page & P. Bommel	2011h, 2012i
20	℔	Echos	Analysing the economic behaviour of operators in the livestock effluent sector in La Reunion	S. Farolfi & P. Bommel	2002a, 2002b, 2003a, 2003b, 2008b
21	Ψ	FireAutomata	Forest fire spread	F. Bousquet	

	Type	Name	Subject	Lead contact	Papers
22	Ψ	Firefighters	Fire brigade organisation methods to extinguish a forest fire	C. Le Page & P. Bommel	2017d
23	℞	FloAgri	“When family farming preserves the Amazonian forest”	M.G. Piketty & P. Bommel	2014c
24	Ψ	ForPast	Transformation processes in a forested area used for grazing	S. Lardon & P. Bommel	1998d, 1998a, 1998b, 1999a, 1999b, 1999c, 2000a
25	ξ Ψ	Griffeath	D. Griffeath’s cyclic cellular analyser	P. Bommel	
26	℞	iLPF	Integração Lavoura-Pecuária-Floresta na Amazonia	A. Burlamaqui * & P. Bommel	2008d, 2012n
27	♣	JogoFogo	Fire risks and smallholder farming in the Brazilian Amazon	E. Coudel & P. Bommel	2013a, 2016a
28	♣	JogoMan	Computer game: Water pollution and property processes in a suburban water catchment	R. Ducrot & D. Adamati *	2005d
29	ξ ℞	MACCA	Replicating an aquifer model by Ravazzani et al	P. Bommel	
30	Ψ	Markets	Analysing the performance West African cereal markets as communication systems	F. Galtier	2002c, 2011g, 2012l
31	♣ ℞	MiRoya	Coffee rust spread and treatment	G. Leclerc & P. Bommel	2019b
32	Ψ	Mobe	Regulating the wood energy industry in Niger	M. Antona	2002d
33	♣	MontyGame	Increasing understanding about errors of judgement made on conditional probabilities	G. Leclerc & P. Bommel	
34	℞	MOPA	Modelling small-scale fishing in Senegal	J. Le Fur	1997b, 1998c, 1999b,
35	℞	PhDModel	Increasingly intensive livestock farming practices in Brazilian Amazonia	S. Plassin *	
36	Ψ	Project Management	The benefits of multi-agent simulation to support project management	D. Medeiros * & P. Bommel	2013c
37	℞	QualiPig	Epidemics in pig farming	V. Porphyre *	
38	♣	Quixeramobim	Water management game, Ceara, Brazil	R. Ducrot	
39	ξ Ψ	Resource Consumption	Competition between agents to use a common resource	P. Bommel	

	Type	Name	Subject	Lead contact	Papers
40	♣	Ribeirinhos	Multi-annual and consultation-based management of two reservoirs in semi-arid Brazil	R. Ducrot	
41	ξ Ψ	Robots Fourageurs	Mineral mining robots	C. Le Page & P. Bommel	
42	♣ ℔	SequiaBasalto	Livestock farmers adapting to climate change in Uruguay	P. Bommel & J. Corral *	2015e, 2014a, 2014e, 2012a, 2012b, 2012c, 2012d, 2012e, 2012f, 2012g, 2012h, 2011, 2011d
43	℔	TransAmazon	socio-environmental dynamics of a Transamazonian pioneer front	T. Bonaudo * & P. Bommel	2010c, 2010d, 2005e
44	Ψ	SIS	The spread of epidemics	B. Bonté & P. Bommel	
45	♣	Teraguas	Computer game: land-use and impacts on water resource quality	R. Ducrot	
46	℔	Thunupa	Adapting quinoa planters to climate change	M. Vieira Pak * & P. Bommel	
47	♣ ℔	VarzeaViva	Multiple uses of an Amazonian flood plain to address global changes	M.P. Bonnet & P. Bommel	2014d, 2015d, 2016d, 2016l, 2017f
48	ξ Ψ	WolfSheep Predation	Population dynamics between prey, predator and grazing	M. Zellner & P. Bommel	

Clearly, I am not going to present all these models but the following section describes two of them that formed part of my work in South America. They illustrate the way in which multi-agent models were designed using the ComMod approach.

6.2. *SequiaBasalto*: Adapting cattle farmers to climate change in Uruguay



Together with Hermès Morales and his colleagues at the IPA (Instituto Plan Agropecuario), we worked for two years (periodically) on a small project funded by INIA (National Agricultural Research Institute) called *Sequia* (drought). Cattle farming is Uruguay's biggest economic earner and climate change is now affecting the sector. Squeezed between two giants, Brazil and Argentina, this small country has more cows than people, with 4.5 heads per inhabitant, giving it the name of the "green desert". The Pampas provides natural pasture land where cattle can graze freely, producing high quality beef for export.

Drought started to occur in the 1990s, resulting in the deaths of thousands of animals and many bankruptcies. To address these changes, the *Sequia* Project sought to boost adaptation capacities of livestock farmers, mainly in the North West region of the country (*Basalto*). The basalt soils in this region (25% of the country) have a very low water storage capacity and are primarily managed using extensive livestock farming systems.

An ABM was developed to test several management strategies and facilitate communication between livestock farmers and support services. The first stage of the design was rather standard as it consisted of designing an ABM with livestock farming and grazing specialists that could represent grazing land growth, herd dynamics and the management by the producers. Two types of agents that mimicked management strategies in a caricatural way were tested. These were the “Productor CC” agent who makes their management decisions by only looking at their herd’s state of health, and the opposite profile, the “Productor Pasto” agent who makes their choices on the state of the grazing land. Researchers and technicians from the IPA considered that “Productor CC” agent fitted the traditional livestock farmer who tries to boost stock density rates by hectare by keeping their animals in adequate condition. IPA’s recommendations go against this as they advise lower stock density rates to maintain good grazing quality (“Productor Pasto”) (Morales et al. 2010, Dieguez et al. 2014).

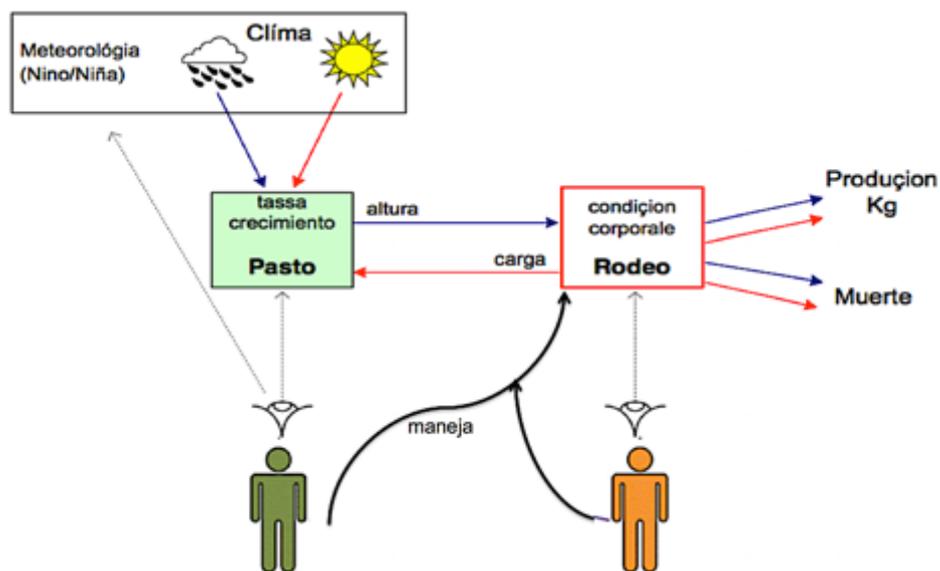


Figure 24: Model principle: The “Pasto” Producer agent takes his decisions based on the weather and the state of grazing land, whereas the “CC” Producer focuses on animal health (body condition).

A first version of the model was subsequently presented to the farmers and discussed in the local area at several workshops. Their main criticism was that agent behaviour was too simplistic and they requested changes to be made.



Figure 25: A) Design session with the specialists, B) 1st workshop with farmers in Salto, C) Livestock farmers assessing the model's UML diagrams, D) A farmer explains a simulation.

After the first version, designed with specialists (photo 21-A), The ABM was presented and discussed with the livestock farmers at several workshops. Photo 21-C shows farmers, both men and women, analysing the activity diagrams of the model. This obviously surprised me! In fact, Hermès Morales who had attended our modelling training sessions in France has subsequently asked IPA technicians to conduct their interviews with the livestock farmers by using this formalism. For several years, the farmers were used to using this type of diagram and could therefore understand those designed for the *SequiaBasalto* model. I then realised it was the opportunity to develop an executable activity diagram editor (xUML, see section 5.7).

We used this new tool in the stakeholder workshops to make the assessment livelier and more effective. Using already available basic activities, the participants could generate new management strategies, without knowing how to programme. Using the xUML editor revealed two interesting features. Firstly, the participants were able to modify agent behaviour and played with the model to better understand its reasoning. The model's immediate response to each modification boosted their understanding of the underlying mechanisms. Many people subsequently recognised that their management ultimately resembled that of a traditional livestock farmer ("CC"). Discussions on the best way to deal with droughts then followed.

The second feature relates to the model's technical aspects. By testing alternatives with the xUML editor, the participants pinpointed specific bias. For example, they realised that in

drought conditions, agents always reacted too late and the decision, for example, to give the herd with feed supplements did not seem to prevent the crisis occurring. The participants understood that agents should act more frequently than just once a season. As a result, the model was corrected by repeating the agents' activities each week. The stakeholders, themselves, could subsequently spot a design error that we, the experts, had not (Bommel et al. 2014).

The outcomes of these group exercises exceeded our expectations. In addition to the discussions that it triggered, the ABM helped identify adaptation strategies that appear to improve the producers' resilience. In particular, the model forced the IPA specialists to acknowledge that their management guidance ("Productor Pasto") was not always the best. Indeed, outside drought periods, the traditional strategy appears to be more economically profitable. Again, the model (even though it was designed by experts) fulfilled its purpose of reviewing knowledge.

After this project, lots of farmers and technicians who took part in the workshops continued to experiment with the model. They use it to research the most efficient management strategies in normal periods and in drought conditions. The Uruguayan government has now adopted the project as a methodological example to follow for other development ventures. Francisco Dieguez, who is currently a professor at the university, and who took part in the project, is now taking a course to learn the ComMod process and multi-agent modelling, to extend the experience.

By way of a conclusion on the Commons, although cattle farming Uruguay is the sum of individual practices on privately-owned land, I take from this experience a vision of agriculture that is not individualistic, but rather driven by a collective spirit. The image of the Gaucho comes to mind; the symbol of the free man of the Pampas, used to a hardy existence, riding roughshod over conventions but poised to protect his poetry, his language, his way of life and his natural environment. Nowadays, this social culture is endangered by the "Siembra Pool", entrepreneurial farmers focused on intensive soya farming and financed by insurance companies or pension funds (Morales Grosskopf et al. 2010, Corral et al. 2008). They seek to optimise agricultural production by the intensive use of inputs and machinery. Faced with these companies that negotiate huge volumes directly with investors, suppliers and exporters, family farms holdings are no longer competitive and are losing their bargaining power. This is a noticeable transformation that challenges the long-term future of traditional producers and is bringing about structural, economic, ecological and social change.

« La relación emocional con la tierra desaparezca o se debilite de manera significativa. Es un cambio de paradigma de valores, siendo uno de los cambios principales que se han dado en las últimas décadas en el ámbito agrario rural.

The emotional relationship with the land is rapidly disappearing or weakening. It is a paradigm change in values, one of the main changes that took place in these last decades in rural agriculture (thesis by P. Arbeletche, 2016)»

6.3. *VarzeaViva*: Defending an Amazonian territory



The Amazonian flood plains, or *Várzeas*, are among the world's most diversified and productive ecosystems. Life is attuned to the annual flood regimes. When water levels are low, the emerging river banks become a vast natural grazing land, where lakes and rivers that concentrate nutrients are ideal for fish breeding. When water levels rise, the river covers these stretches of land once

again, enabling different species to mix and silt to be deposited on the soils.

Communities have lived in this area for several centuries (initially Amerindians then mixed-race colonies called *Ribeirinhos*) and have learned to live with these environmental variations. When the waters recede, people plant manioc in the fertile silty fields and lead their herds to the grazing lands. At high water, they gather their livestock on rafts tethered to their houses on stilts and give them cut fodder, while fishing is the main activity in the shoulder seasons.

During the last thirty years, irregular rainfall and deforestation in the Amazon have caused the river's hydrography to change, with higher, even exceptionally high flood waters. These relatively rapid changes are disrupting traditional production systems and making families more vulnerable. Uncertainties concerning the arrival of the rains, or the intensity of flood waters makes developing long-term strategies very challenging. Prolonged and extreme flood waters are forcing livestock farmers to open up more grazing on dryer land, which is, in turn, leading to environmental degradation.

Although several studies describe these hydrological changes in the Amazon, relatively little information exists on adapting communities to these phenomena. The *Clim-Fabiam* Project, funded by the FRB (French Research Foundation for Biodiversity) sought to understand how local communities were adapting to this changing environment and, in turn, how their practices affect aquatic biodiversity. By assembling a multi-disciplinary team, we wanted to combine hydrology with water biochemistry and planktonic flora and compare them to the perceptions of local stakeholders as well as the strategies they were developing.

The project focused on the "Lago Grande de Curuaí" flood plain, an area with a population of 30,000 spread out in 133 communities, governed by the Prefecture of Santarém (Pará State, Brazil). The area is highly representative and the population is isolated from the big cities of the State of Pará, while access to public services is limited.

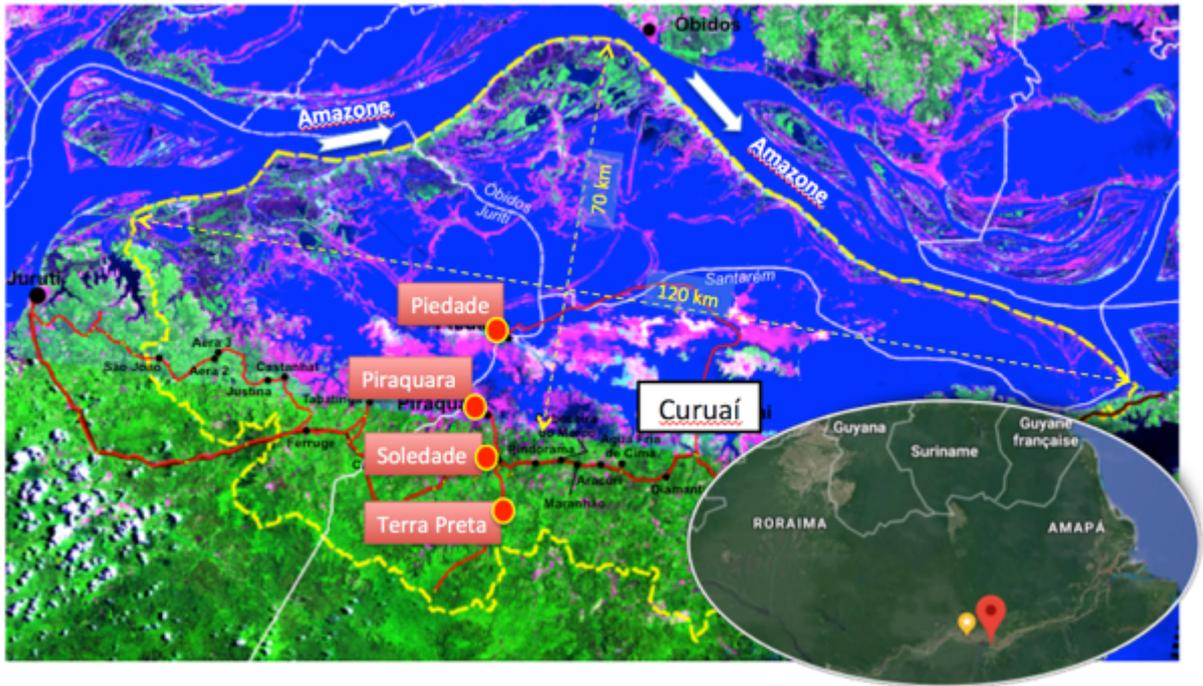


Figure 26: The “Lago Grande de Curuaí”, Pará State, Brazil. The 4 communities where participatory modelling workshops were delivered have been added to the map, along a Forest → Lake transect.

In this region, the INCRA (National Institute of Colonisation and Agrarian Reform) is responsible for separating public land from private. However, due to a lack of resources and mounting complexities, the land has been allocated without any real boundaries, nor separation between what is public and what is private. Without title deeds, local communities only have a right to use the land, although, in practice, land is commonly sold. Given this legal uncertainty and after a long campaign to rally the local population, INCRA finally created a PAE (Agro-Extractivist land register plan) in 2005. It is managed by the *Feagle*, a non-governmental organisation that represents the communities in the local area. It is tasked with monitoring agrarian reforms and links between institutions, communities and social bodies. It is also in charge of natural resources by issuing authorisations to clear forests and hunting and fishing permits. Now, the future of the PAE, which was responsible for managing property and land-use conflicts, is in doubt. Indeed, regional conflicts and pressure exerted by mining and timber companies, coupled with the complex land ownership situation is threatening the renewal of its remit.

Through a partnership with the *Feagle* and a rural family school in Curuaí, we were able to engage with local communities and ask them to work together on these challenges. An initial phase of surveys and interviews in several communities in the region helped to produce an initial assessment of the local area (Fig. 27). We then chose to focus our work on a small area of four communities that represented the range of rural activities around the lake: *Piedade*, a fishing community on the *Várzea*, *Piraquara*, a lakeside community mainly involved in



livestock farming, *Soledade*, 10 km from the lake, on the *Trans-lago* (the road that connects the entire region), and *Terra Preta*,

at 20 km from the lake where new land had been opened up in the forest.

We worked with the rural school that taught vocational courses to young adults who were already involved in their local communities. As well as introducing them to our scientific activities, they helped us better understand, more informally and spontaneously, the main concerns in the region.



Figure 27: Studies and workshops carried out in the communities to understand the changes and rural practices, as well as to develop a territorial assessment.

Given the noticeable vulnerability expressed by the stakeholders, we began by studying their ways of life and their rural activities in each community. Then we discussed their concerns and possible scenarios. This participatory approach required careful listening and consideration given to local worries. As mentioned in the introduction, “true questions about development take shape by tapping into the stakeholders’ experience, at the risk of **revising initial objectives**”. This occurred in this project where the initial objectives, which were more focused on biophysical questions, were changed. Originally, hydrologists and biologists had asked the question: “Could the research findings on hydrology in the flood plains enable local communities to better plan for variations in the river, to adapt their activities and be less vulnerable to changes?” Our support process reversed that outlook to start a dialogue with the local communities to identify the concerns and strategies of local stakeholders and what they expected from the researchers.

The workshops revealed that the difficulties were not just linked to climate change. Other socio-economic and demographic changes were also happening. For example, population

growth had a significant impact on the environment. Without waste water treatment systems, this growth was causing a mushrooming in aquatic micro-organisms.

The project's chemists and biologists showed that there was an increased presence of cyanobacteria and this growth presented a threat for human and animal health, as well as for fish stocks already threatened by commercial fishing and the flouting of community fishing regulations. The participants often expressed the general feeling on these issues, that the authorities and local bodies were not listening to them.

To address these new questions, as well as facilitating and developing more in-depth discussions, a role-play game and a hybrid ABM were designed with students, producers and *Feagle* members. A board game called "Varzea Viva" was firstly designed and tested with students to match the context of each community (Figure 28-a). It was reconfigured in the second stage to represent the entire transect and was played by gathering together the 4 communities. Playing their own roles, the participants exchanged services and goods, while performing actions that altered the landscape. The game subsequently delivered a relatively realistic scenario for a potential future. Difficulties encountered were discussed in the debriefing sessions and related to the problems really encountered on the ground. However, manipulating numerous pieces in the game took time, which meant that a simulation could not be run for more than 5 years, yet ecological processes or the concentration of pollutants can only be observed over long periods. These constraints led us to convert this role-play game into a hybrid simulator to extend the sessions into the long-term. This perspective, supported by the ABM resulted in several moments when players realised the effects of everyone's actions on the local area and on the quality of life of the Ribeirinhos.



Figure 28 : Game sessions. a) Board game, b) VarzeaViva grid in Cormas, c) Screening the ABM on a board with pawns to represent the players, d) Participants gathered around a horizontal projection of the hybrid ABM, e) User interface to decide on activities for the year.

This Amazonian case study started a thought process on the **ethics** of assisting areas as the question quickly arose of whether to include external stakeholders whose actions also affect the degradation of the local area's resources. These are commercial fishing operations that come in and fish the lakes, but also include Fazendeiros (large cattle ranchers) that send huge herds to the Várzea, large soya producers looking for flat, fertile land, or mining companies wanting to mine local bauxite deposits. All these stakeholders are pressurising local leaders to buy land.

Although the local communities can do very little in terms of climate change, they are adapting their activities and practices. However, they feel much more vulnerable to large-scale socio-economic pressures. It is not the inevitability of change that concerns them but the fact that they don't have a say in their own future against economic and political forces that override them. They consider this unfair.

The issue about whether external stakeholders should participate is methodological, but also touches on ethics. The aim is not to pin the blame for the environmental degradation on external stakeholders that are not part of the discussion, nor is it to point the finger at the practices of those taking part. Given these questions, we asked for a non-neutral stance to foster equality and sustainability. Apart from technical questions on the modelling process, these power games must still be considered and how to accommodate powerful stakeholders, while building the capacity of the most vulnerable (Barnaud et al. 2010, 2017). Speaking for

the project researchers with one voice, our implicit and common goal was to protect the most vulnerable who are also in the front line of these changes.

In the Amazon, far from administrative centres, social violence is part of everyday life and the pressures exerted on the weakest are frequently radical in nature. By inviting certain stakeholders to participatory workshops (if they accept taking part in this type of dialogue), we were potentially inviting more violence. If we ignored the asymmetric nature of power, we might exacerbate inequalities by allowing those wielding most power to exert greater influence on the outcomes of the participatory process that advantage them (Barnaud and Van Paassen 2013). The choice was therefore made to only involve local stakeholders, to get a better grasp on the ongoing processes and implement a participatory outlook-orientated approach. In fact, supporting local stakeholders to introduce community regulations that safeguard their living conditions is already an ambitious target. By helping them look ahead to the medium-term, the process helps to take a step backwards and comprehend the effects of everyone's actions on the local area. Very much aware about ongoing degradation, several stakeholders asked to toughen rules and controls on fishing or to set up a collective management system for forests. By providing institutions with scientific documentation on the state of resources and by contributing to social cohesion, the process seeks to build the negotiation capabilities of the most vulnerable stakeholders (Bommel et al. 2016, Melo, Coudel, and Bommel 2014, Bommel et al. 2012).

7. Training sessions

I would like to conclude this overview of my work by emphasising that model design training forms a significant part of my activities. When I joined GREEN, I added an annual training course initially designed by F. Bousquet and C. Le Page. The aim of this two-week course entitled, “ABM and complex system simulation: Applications for renewable resource management”, was to introduce multi-agent simulation to non-computer specialist students and researchers and train them using Cormas. The format focused on presentations on the key concepts involved in agent-based modelling, using demonstrations and model manipulations with Cormas. Then, in small groups, the participants set up a prototype to deal with a subject of their choice. Part of the training was therefore focused on learning to code in Smalltalk. As the courses progressed, we also created a library of training models (cellular automata, game theory, coordination modes between agents, networks, spatial aggregation concepts, aquifers and hydrographic networks, etc.). Since then, we now use several models for tutorials, such as the *ECEC* model (presented on page 24, which is a replication of the model by Pepper and Smuts, 2000), or *Firefighters*, which illustrates how a forest fire spreads that must be tackled by a brigade of firefighters.

When I joined Cirad in 2001, I asked to add a UML module to the model design training courses. The reason for this was, at the time, participants switched directly from a brief description of their conceptual model to coding their simulator. I also used this course to get non-computer specialist participants to understand object concepts. This part of the course replaced the module on learning Smalltalk. Nevertheless, in their assessments, most

participants though that the UML module was especially important. They highlighted the benefit of learning this formalism process to fully grasp object concepts and design models individually or in groups (for example, an object diagram editor in Cormas helps to visualise an agent in a simulation, as well as all the entities it is connected to, see Figure 16, page 41). Computer coding the model then becomes a practical task that is gradually mastered but doesn't necessarily interest all the participants.

As I explained in my CV, I have jointly organised 22 “International Training Programme on Multi-Agents Systems for Natural Resources Management” training sessions, most of which have been run abroad. These training sessions (sometimes two a year) were tailored to modelling beginners who wanted training in Cormas. From 2011, we amended the format by adding other simulation platforms, such as Mimoso, Netlogo and Gama. Now called, *MISSABMS* (“Multi-platform International Summer School on Agent-Based Modelling & Simulation”), this two-week annual training course, run in Montpellier (8 sessions since 2011), attracts participants from a range of countries, which makes for highly stimulating exchanges. In week one, they learn basic ABM concepts that are illustrated on various platforms. They also become familiar with the platforms proposed by the course (we highlight the strengths and weaknesses of each one) and choose which one they will use for the group work in week two. The training courses generally attract an average of 22 participants per session and they tend to use each of the three platforms in equal numbers. Even if there is sometimes friendly competition between the trainers who each promote their platform, this new format certainly forces us to understand the problems encountered by beginners in model design and the way each platform accounts for this. My personal view is that we shouldn't only consider each tool's technical advantages (GIS, distribution, interactivity, etc.), but also how to gauge the level of difficulty modellers encounter when they try to implement their model on a particular platform. These training sessions also help us develop a list of models implemented on all the platforms and to compare how they perform in relation to on another, together with any observed anomalies. This gives us concrete facts to discuss replication problems (Hales, Rouchier, et Edmonds 2003, Le Page et al. 2017).

In addition to about 30 training sessions, I have also organised and delivered training modules on my own in Brazil (5 sessions), Uruguay (5) and Costa Rica (4), with an average of 20 students per session for one week.

Although my courses focus on ABM models, I try to feature other modelling tools, such as differential equation systems, to give a broader view of modelling, as well as showing the pros and cons of each paradigm.

When running these training courses, I think it is vital to go beyond the purely technical aspects and discuss the role of models and questions that underpin their validation. The position the modellers takes must also be covered, especially in collective design situations. On this point, (Drogoul, Vanbergue and Meurisse 2003) split the modelling stages into 3 roles: (i) the thematician designs the model domain, (ii) the modeller provides a model design meant to eliminate ambiguities from the model domain description and, (iii) the computer scientist who comes up with an operational model (independent from all computing

language), which serves as a basis for implementation. The modeller's role is seen as a mediator between the two specialists and requires a subtle understanding of model design (or co-construction) and implementing a simulator. This does not mean that these three people have to be in place as a bare minimum to develop a multi-agent modelling project, but at least one participant must fulfil these roles. In practice, the lead partner in a ComMod process often takes on all three roles. For development projects in outlying areas, the modeller often runs workshops with local stakeholders. Combining these roles has the advantage of better communication between roles and greater continuity in interactions with thematians and development stakeholders.

8. Research project

“Researchers can also do something newer and more difficult: encourage the appearance of organisational conditions for the collective production of the will to discover a political project and, secondly, the organisational conditions for the intended success of such a political project: which will obviously be a collective project”

P. Bourdieu, “For an Engaged Knowledge”, *Le Monde Diplomatique*, Feb 2002

8.1. Targeted research on “the Commons”: what connects us

“I would rather address the question of how to enhance the capabilities of those involved to change the constraining rules of the game to lead to outcomes other than remorseless tragedies”

Elinor Ostrom

The tragedy of the commons, a hegemonic model

Garrett Hardin, a Professor in Ecology at the University of California UCSB, published his renowned article, “The Tragedy of the Commons” (Hardin 1968), which describes the tragic conflict between individual interests and the commons. In addition to the academic sphere, this article considerably influenced economic and political thinking. His model is based on a thought experiment where cattlemen use a piece of common pasture land to graze their cows. Each one wants to add a cow to fatten it and make more money, but each additional cow eats into the increasingly fragile source of fodder and all together, they get a little less grass to themselves. This negative effect applies to all the cows, whereas the profits from selling one additional cow only go to its owner. This is the famous “privatising profits and socialising losses” scenario. As his individual benefit is positive, each cattleman is tempted to increase his herd on common land. With each extra cow, the land becomes over-grazed and the common is ultimately destroyed. “Even if they are aware of the impending disaster, the cattlemen are caught in the relentless logic that causes them to destroy the resource that makes their living” (Hardin). Using the “what is not caught by me will be caught by others” logic (Janssen, Bousquet and Ostrom 2011), Hardin deduces that “Freedom in the commons brings ruin to all”. Just like the prisoner's dilemma, so-called rational individual actions lead to a paradox, i.e. irrational outcomes, collectively. To counter this effect, Hardin offers two

alternatives: splitting the land into private plots (each owner managing their plot with due diligence) or the appropriation and regulation of this common by the State, which sets the rules, quotas and access rights.

The article made a lasting impression and all American students must have read it²⁷, given that the text is used by academic circles, the media, administrations and neo-Liberal political figures use it as scientific justification to privatise resources and ecosystems. Yet, many cases show that “*private property can easily lead to pillaging resources when capital is mobile. Seeking efficiencies leads me to destroy more quickly and move my investment*” (Weber, 1995). This applies, for example, to deforestation in the Amazon or the intensive use of inputs to grow soya in Argentina, (see section 6.2). Furthermore, Hardin’s argument is only valid if we assume that it concerns only livestock farmers acting solely out of their strict self-interest, i.e. greed. Being purely individualistic, they cannot communicate to create forms of organisation to regulate use of the grazing land. Hardin confuses what he calls “*the commons*” with situations of *free access* where everyone can use as much as they see fit (Berkes et al. 1989). However, the term, “the Commons” also means other things. It refers to systems of organisation (institutions) that communities use to manage and live from shared resources. There are many cases where collective assets are managed, often very sustainably (pastures, water resources, forests, fisheries, etc.). Also, these resources are “managed by individuals that communicate and part of whom is not guided by a close interest, but instead, a collective sense” (Hervé Le Crosnier in Petitjean 2010, p.20).

It should be noted that models can be used poorly by taking those models that fit what we want too literally. In Hardin’s case, his model “plays a key role in the action of persuading the public that “liberalisation is a good thing” (Boussard et al. 2005). In a historical analysis of Hardin’s work, F. Locher (2013) goes further. He explains that the biologist became a fervent post-war supporter of the neo-Malthusian cause, thinking that demography had to be controlled to manage resources. His article on Hardin primarily seeks to denounce the unrelenting mechanism that pushes people to reproduce without restraint until natural resources are destroyed. “In his metaphor, the cattle that the farmers continually add to the pasture are themselves the offspring of these same cattlemen, who increasingly deplete the common assets. This is why he also recommended two solutions: either State control on human reproduction, or by creating monetizable and tradable « birth rights ». This is a combination of State coercion and market ideology that epitomised the cold war dogma” (ibid.). In 1950, Hardin said he was in favour of sterilising the feeble-minded. In line with his ideology, he subsequently campaigned against food aid in the third-world due to its counter-Malthusian effects. Until his death in 2003, he focused his efforts on combatting immigration.

Experimenting with the tragedy of the commons using the Fishbanks game

In most of our training sessions we organise a game on day one that helps us address resource management. As a result, I have run some thirty Fishbanks sessions. The game involves a

²⁷ “In many environmental science faculties, most (at least in the United States) students can study Garrett Hardin’s article three or four times before completing their studies” E. Ostrom, cited in Antona & Bousquet (2017).

computer-assisted interactive simulation (see section 4.7), in which the players form fishing companies that they must manage (Meadows and Meadows 1993). The participants have to maximise their capital in an economically competitive virtual world by exploiting renewable resources. Following the submission of his report to the Club of Rome entitled, “The Limits to Growth” (Denis Meadows et al. 1972), Dennis Meadows created Fishbanks in 1986 based on G. Hardin’s article, to illustrate “The Tragedy of the Commons”. Starting with free access to two populations of fish, the game irremediably leads to a crisis due to overfishing. Although certain players foresee the environmental crisis at the start of the game, most of the time they are caught up in the chase to find the biggest shoal of fish. The facilitators sneakily fuel this by regularly offering various types of boat auction sales. Eager to compete, the players forget what supports their livelihoods and when fish stocks collapse it is often too late (there is a long regeneration period when fishing is banned before the players can regain adequate yields).

In a game session, crisis management leads to lively discussions that often result in negotiations on quotas or fishing efforts. The biggest fishing companies generally want rules on the number of boats to be left in port, while the smallest prefer rules of proportionality. When an agreement is made, it is not unusual to see players flouting the collectively approved rule. The shock of such traitorous behaviour leads to new negotiations that often result in sanctions. Broadly speaking, the game runs through different stages, from a competition based on individualism, developing a joint assessment and introducing access rules, control systems and sanctions decided by the group.

The game debriefing session enables everyone to say what they feel and describe how they experienced the principles of community-based resource management. A more in-depth description of the game can then be used to describe the underlying model and compare the results with the Gordon-Schaefer model (1954). We can subsequently illustrate the big differences between the mathematical models by these two researchers and the results generated by the game. The differences are due to equilibrium assumptions required to resolve equations²⁸. Apart from its entertainment value, the main benefit of this game is to inform the players that capitalist²⁹ management of a common resource irremediably leads to a collapse of the system, whereas agreements between stakeholders secured from tough negotiations help maintain system viability.

Real alternatives to “Governing the Commons”

In 1965, the American political scientist and economist, Elinor Ostrom (1933-2012), defended her thesis on political science at UCLA. The subject was managing a Californian

²⁸ To be balanced, only the quantity of fish produced by the fish stocks during a given period of time should be caught ($dP/dt = 0$), however, without mentioning the many other interactions, it is rare to encounter such situations. At least this is what the game tries to highlight.

²⁹ The “winning” financial strategy is to invest massively in a large fleet of boats at the start of the game, even if it means paying bank interest rates, to make the most of the godsend provided by the abundant fish stocks. Then, when the stocks show the first signs of change, sell or even give away all your boats to become an eco-responsible company. This is clearly a purely capitalist, unsustainable strategy but which reflects numerous similar cases in the real world.

aquifer. The aquifer was being over-exploited, prone to salt water salinization and its many users were faced with a collective action problem: everyone was being pulled into a race to pump the water table and without any coordination between the users, this resulted in it being over-exploited. Elinor Ostrom was sceptical of Garrett Hardin's work, which affirmed that a group could not find a solution to the problem. She explained in her thesis how the farmers managed, despite the odds, to find a solution by using public (courts) and private (user associations) decision-making arenas to build agreements that would regulate their usage and invest in technical solutions to replenish the aquifer. The tragedy was therefore not irremediable, contrary to popular theory at the time.

Hardin's reasoning is based on an ideological vision of the world (see section 2.2 on the non-neutrality of models) that ended either in State management or individual ownership operating rights. In response to Hardin's framework, Elinor Ostrom showed that there was a "third way" (Antona and Bousquet 2017) to govern the commons, by self-governance or self-organised management³⁰. In her best-selling book, *Governing the Commons* (Ostrom 2015), Ostrom criticises conventional economic theories applied to natural resources. She also shares successful and unsuccessful experiences of governing the commons to develop "the best intellectual tools" from these case studies. These tools are designed to chart out the capabilities and limits of independent communities to govern their own resources. At the same time, she explains that there is no "reference list" or single definition of the commons. Each common stems from unique historical circumstances, local culture, economic and ecological conditions, etc. Her aim was to develop a collective management theory for the commons based on the empirical study of local "self-governing" commons. She sought to highlight the design principles to foster the emergence of sustainable collective management but by immediately adding that if context was not considered, its *Institutional Analysis Design* (IAD) framework becomes sterile dogma.

Ostrom highlights seven basic principles for her analytical frameworks: 1) define clear group boundaries, 2) match rules governing common goods to local needs and conditions, 3) ensure that those affected by the rules can participate in modifying the rules, 4) make sure the rule-making rights of community members are respected by outside authorities, 5) graduated sanctions, 6) accessible means for low-cost dispute resolution, 7) minimal recognition of user rights to design their own in institutions. There was also an 8th principle, a multi-tiered organisation for more widespread and complex resources. Furthermore, she analysed how institutions emerged and evolved by negotiation and studied cases of commons management failures by highlighting the importance of the political circumstances. She subsequently defined the key elements behind the development of these institutions, which were **reciprocity** and **trust**. Elinor Ostrom, won the 2009 Nobel Prize in Economic Sciences, for her work on systems of rules for organising these commons.

³⁰ E. Ostrom ironised on the expected role of scientists: "As scientists, we are meant to create models, find new paths for reflection and research the optimal solution in our models and theories to then recommend whether property returns to the private sector or the government. We can assume that users are not going to resolve this second order dilemma, i.e. find new rules that they would apply to themselves. Already, they can't resolve a first-order dilemma that of each person, individually, reducing their operating activity. Our role is therefore to develop models that can be used to resolve the problem and as such, many scientists have become very, very proud of this role". Ostrom, 2011, cited by Antona and Bousquet 2017, p. 32).

“Her work in experimental economics helped understand the role of key variables in collective action and social dilemmas, such as information, face-to-face communication, trust, interaction and knowledge about the resource” (E. Brondizio, preface for Antona and Bousquet 2017).

Conclusion: Towards research to support the collective management of the commons

Natural resource management methods based on the commons must not only be defended on behalf of communities that live from them and depend on them, but also because they embody a viable resource management model, not just locally but globally too. We could go as far as to say that it is because “natural” resources (land, agriculture, forests, water, seeds or fish) are managed locally as the commons that they can also be safeguarded as the global commons” (Petitjean 2010).

Economic science and politics have long ignored the question of the commons, as demonstrated by Margaret Thatcher’s “There is no alternative” stance. However, it can become a major “tool for thinking” (H. Le Crosnier, in Petitjean 2010) and it is subsequently in this sense that I want to **direct my research** and develop modelling tools for these processes.

The aim is not to develop a generic model to demonstrate ways of securing social cooperation, because, as Bruno Latour and his colleagues explained, *“Social simulations fail to obtain these arrangements, because they disregard the subtle mechanisms that govern the establishment of trust needed for cooperation. As shown by Ostrom, common standards, family ties, reputation and even facial expressions are crucial to obtain social cooperation. Impossible to anticipate through conceptual models, these factors can only be revealed by empirical observation”*. (Venturini, Jensen and Latour, 2015).

In contrast to researching a management model for the commons that might result in a “sterile dogma”, my future studies will target further improvements to modelling and interactive simulation tools. But above all, I will seek to enhance the methodology by strengthening the ComMod approach and raise awareness on the field about the need to manage the commons in a fair and viable way.

8.2. Developing tools to support the management of the commons

As I am in charge of developing Cormas, I described the features on this platform (Bommel, Becu, et al. 2016) and the specific niche that it occupies, i.e. collective model design and interactive simulation (or hybrid simulation, Le Page et al. 2014) that combines decisions made by the players and others by agents in the model. By omitting research and development projects (that require lots of time and presence on the field but which depend on responses to calls for proposals from sponsors), this section focuses specifically on the work that I intend conducting to develop modelling and foresight tools to facilitate mutual understanding between stakeholders and support the management of the commons.

Cormas in 10 years!

During the 2nd virtual CoMSES³¹ conference, in 2018, Marco Janssen, Director of the “Center for Behavior, Institutions and the Environment” at the University of Arizona, invited us to present our future vision of the Cormas platform (Bommel et al. 2018). It marked the opportunity to consider the guidelines that we, the developer team, would like to see change on the Cormas platform. The article below presents an abstract, a video session and series of questions, with answers available on the CoMSES website:

“Cormas is an agent-based modeling and simulation platform that deals with interactions among stakeholders about the use and management of renewable resources.

The philosophy is to use the platform with people who are not specialist of modeling. The development of the platform seeks to support the Companion Modeling approach (ComMod) – an original form of participatory modeling. The aim of the models and simulations built with the platform is to promote a shared vision of the system by taking into account the different viewpoints and concerns.

With Cormas, in 10 years, we want to have more responsive human-computer interactions. We will be able to use interactive gameboards with tangible objects during a participatory simulation, as well as multiple devices in to order to smoothen the way participants interact with a simulation. This will encourage spontaneous behavior, expression of emotions and empathy for more lively and interactive simulations.

Collective design using executable UML and software blocks will be important innovations for making model development accessible to non-modeler. Artificial intelligence and high performance computing will be used to enhance hybrid simulation and model exploration. The aim is to be able to change the model and to explore all the possible trajectories of a simulation during the course of a participatory workshop with the stakeholders.

In short, the development of Cormas in the 10 coming years will focus on the meaning of the model and on the interactions among participants ».

M. Janssen challenged me during the conference: “You mention not to go to 3D simulations. With the advanced technologies in the future why not provide the stakeholders more detailed simulations? Could you expand on that?”

I answered as follows: “Yes, our objective is not to go towards more realistic simulations. I didn’t say that we will never use 3D representations, nor immersion glasses (who knows what the future will be like!). But we do not focus our work on this type of development. We are not necessarily looking for more realism. Why?”

Because a model (or simulation) is only an artifact that allows a group of participants to project themselves into the future, but above all to debate the orientations of this given collective.

³¹ CoMSES (Computational Modeling for SocioEcological Science) is an international network of researchers and professionals with the common aim of improving the way we develop, share and use agent-based modelling in social sciences and ecology. CoMSES also hosts the openABM website to promote good practice and which it uses to gather ABM models to safeguard, catalogue, replicate and re-use them.

We must therefore not try to dazzle this collective with high-tech tools, but rather to produce a representation of the socio-ecological system that is transparent and understandable. Our concern is that presenting high-tech tools may overly impress the participants, which would prevent them from questioning the structure of the model and the behaviour of the agents.

The criticism and revision of a model are the very driving force behind a dynamic learning process. From the “KISS” to the “KIDS” approaches, we give priority to the KILT approach: Keep It a Learning Tool (Le Page and Perrotton 2017)!”

Indeed, counter to current trends, the aim is not, initially, to invest in 3D modelling, nor to use LCD video glasses and headsets for immersive simulations. The main aim is not to have more realistic simulations where the “high-tech” results can overwhelm users and boost the model’s “black box” (Horlitz 2007, Gurung, Bousquet and Trébuil 2006)³². Conversely, simulation participants must understand that the model is just a crude imitation of their system, an ertzaz of their reality so that they always feel they have the right to criticize it. Because the objective is not to work towards more realism, but to see the model as both an artefact (a "macroscope" would say Joël de Rosnay) that provides a global vision of the system and a perspective on the ongoing processes to explain the reasons for a crisis, as well as an object of mediation to encourage dialogue between stakeholders.

The preferred course for Cormas remains stakeholder interactivity. This is why the main effort will be channelled to man-machine interfaces and ergonomic design. For example, we will develop an extension to control the movement of agents on the spatial grid using tangible objects that can be physically moved on a table. This development will use digital recognition technology for QR codes that will be printed on the undersides of the physical objects. By projecting the spatial grid on a table, this extension will be used in hybrid simulations combining virtual and real objects. All these improvements will occur in parallel with concrete experiences on the field involving local stakeholders to provide significant contributions on social and environmental issues.

Cormas Pharo

“Sharing and learning-by-modelling generate
empathy and mutual understanding”
(Bommel, Bécu, Bonté, Delay, Le Page, et al. 2018)

We have begun the major task of switching Cormas over from VisualWorks (VW) to Pharo. These two languages are two implementations of Smalltalk, but in contrast to VW, Pharo is available on a free licence. When Cormas was created, VW was developed and maintained by Xerox PARC, then ParcPlace Systems and subsequently taken over by Cincom. Although it is an open-source and free software application in its “non-commercial” version, VW does not have a truly free or “copyleft” licence that gives users the right to modify a software

³² Gurung et al. (2006) also explain that “Realistic representations prevent the stakeholders from taking a distance from reality (and interpersonal conflicts, etc.)”

application and reissue it. We currently feel trapped as Cincom has virtually stopped investing in its proprietary software. Also, it now only comes in a ‘trial’ version of VW and the VW7.6nc version that we use is no longer available on the American company’s website.

While VW is an excellent application of Smalltalk, for the aforementioned reasons, we decided to switch the development of Cormas to Pharo, a free software application licensed under “MIT” (Cormas is on the same licence).

Like VW, Pharo is a dynamic programming language whose main advantage is that all the code doesn’t need to be recompiled when a method is modified. This feature comes into its own with the Pharo debugger to stop an execution flow, inspect parameter values, alter instructions, create new methods and then resume the execution flow. Compared to conventional “edit, compile and run” functions, this feature makes the learning process easier and is a major advantage for apprentice modelers. By entering the debugger, they gain a greater understanding of the way their code proceeds, can check instructions and their logical outcomes and point out objects in their model. The object concepts become clearer and more coherent. Without quitting the debugger, they can then continue coding their model (“Live coding”) by instantly checking that each stage is robust (“direct model checking”). The reflexivity of the language also lends itself to creating learning agents able to modify their structure and behaviour while the simulation is running.

The switch to Pharo is also an opportunity to join up with a keen and active community of developers who appear to be welcoming the arrival of Cormas with real gusto. This is what we felt when we took part (Bommel et al, 2018³³) in the latest ESUG Conference (European Smalltalk User Group) that brought together most of this community. Several developers have started working on the new version of Cormas (<https://github.com/cormas/cormas/>). Based on our recommendation, Cirad joined the Pharo Consortium in 2019.

Given that Pharo works on IOS and Android, we are developing a smartphone version of Cormas to facilitate user-player interactions with a collective simulation (as even in the depths of the Amazon, with no telephone network nor internet, young people all have Smartphones!).

To help thematians implement their models, the Cormas-Pharo developments focus on designing user interfaces to automatically generate part of the computer code. A class diagram editor that generates class code, attributes, and links is also available (Uhnak and Bommel 2016) but it still needs to be improved and added to Cormas-Pharo.

We are also developing a more comprehensive activity diagram editor for handling variables. The modeller will define decision points by graphically describing the test using the model parameters and logical operators. These activity diagrams, with input and output parameters will be useful to define more complex operations. That said, non-scientific stakeholders will find using this tool a challenge.

With the switch to Pharo, the GIS component will have its hands full displaying *OpenStreetMap* data and other geographical databases but while it is useful (and frequently

³³<https://hackmd.iscpif.fr/p/By-9IVqfQ#/>

required) to display and use a vectoral map in Cormas, users can quickly find themselves hampered by the static look of a GIS system. Users often ask to see a map but if the landscape cannot evolve, if it remains frozen in time, it is better to come back to a raster system to allow plots and forests, for example, to expand or shrink. One of the avenues of research that we are working on will be to design deformable spatial entities to gradually transform a landscape under the simultaneous action of agent activities and the natural processes of the vegetation cover.

8.3. UML, the interdisciplinary modelling language

As explained in section 7 “Training sessions”, I place great emphasis on formalising models into UML diagrams in the multi-agent modelling courses. In the 19 years that I have been regularly teaching this UML module, I have gained specific expertise in this subject by reviewing and amending course content to help non-computer specialists understand object-based concepts. Course evaluations indicate that the UML module is especially appreciated by the participants³⁴ as they see the benefits of mastering this formalism to publish their models and for the individual or collective design stage.

The design stage of a model should be regarded as the preferred stage for dialogue between experts, thematicians, development stakeholders and occasionally, computer scientists. It should be conducted with simple, unambiguous illustrative tools to bridge disciplines. As a result, with reference to Morand (2000) “the diagram is central to the cognitive process and not peripheral”. From a “thought by diagram” perspective, UML becomes a genuine language to represent knowledge (Bommel and Müller 2007). It should be seen as a universal language that brings disciplines closer together.

As I position myself in the Constructionist approach, I think that knowledge and its various representations are social constructs with their own legitimacy and limits to their validity. As such, the various disciplinary discourses as well as those of the stakeholders become as many points of view on a reality. These then need to be clarified and focused on a mutual issue that is, itself, a construct.

In addition to a simple design tool, UML can play a key role to facilitate dialogue between disciplines. But to this end, the modeller must also be a facilitator. In order to enable this collaboration between disciplines, it is necessary for the interlocutors of the various themes to travel part of the path that too often separates them. It is essential that everyone be able to express themselves in a language that is accessible to others, if only to fully grasp the limits and potential of everyone’s respective approaches. In these circumstances, the modeller must facilitate exchanges and turn everyone’s proposals into a coherent, conceptual model that is understood by all.

So, if participatory modelling effectively promotes the reciprocal understanding of disparate points of view by attempting to provide a clear, well thought-out and above all shared

³⁴ Many training course participants have recommended I write a book about the course, giving examples related to agronomy and natural resource management, as well as implementing them in Cormas, Netlogo and Gama.

synthesis, it still remains to propose a listening posture and practical methods to guide the modeller to lead this maieutic process. Being able to express knowledge in scientific and laymen's terms appears to be the most advantageous stance for transdisciplinarity.

8.4. Simulation and forum theatre: What if I had done things differently?

Forum theatre (FT) was developed by the Brazilian, Augusto Boal, and is a form of theatre that allows for exchanges, interactions and consideration with the audience. It was trialled in the favelas of Sao Paulo in the 1960s and has proved to be an effective tool to consider antagonistic points of view, as well as for finding solutions to social and personal problems. Also called "Theatre of the Oppressed", Augusto Boal invented FT to enable excluded sections of the public to have their voices heard and speak freely.

Each FT session generally has two parts. The first is an "exposure", where actors on a stage portray a situation of oppression or a genuine social or economic problem. In part two, "audience involvement", the spectators are asked to give their opinions on the scene played by the actors. A facilitator then offers to re-enact the scene by replacing some of actors with members of the audience who can influence how events proceed.

This is therefore a form of participatory theatre in which the spectator and the audience become actors to propose and test alternative forms of behaviour to resolve a problem. Supported by François Bousquet, this theatre technique is now being trialled by the GREEN unit in some projects.

Forum theatre does have links to interactive simulation, where the participants' actions can influence how a multi-agent simulation proceeds. The tools developed for Cormas, such as the xUML activity diagram editor, help describe an agent's general behaviour (see section 5.7). As a result, it is possible to modify an agent's activity diagram during a simulation to see how their new behaviour influences the overall process (Bommel, Becu, et al. 2016).

Like forum theatre, which collectively explores scenarios, a Cormas simulation also enables participants to 'travel' through a simulation (section 5.8). Using tools such as "time traveling", participants can go back in time ("backwards") and take up a position at a specific moment in the simulation. The same scene can then be replayed ("forward") or to start again from this point by experimenting with alternative forms of behaviour.

These tools, which have only recently become operational, have not yet been tested in the field, i.e. in workshops with development stakeholders. They still need to be refined to become proper tools for learning by experience but given their commonalities, it would be interesting to consider the ways to combine forum theatre sessions with interactive simulations using Cormas.

8.5. Conclusion: Transmission

In addition to the models developed, my experiences of co-constructing models when stakeholders are given support, have highlighted the importance of the modelling process per se. It is important to generate, share and incorporate knowledge but also to facilitate communication, coordination, negotiations and learning. In the next few years, I will be focusing more on social learning and the ways in which modelling can support the development agreements between stakeholders of a socio-ecosystem.

This work will involve research and development projects on a range of issues in various geographical locations. I will however strive to work on subjects that particularly affect the collective management of resources, in order to strengthen the capacities of more disadvantaged stakeholders and try to develop other paths than the one that leads to tragedy.

To conduct this research, I will continue to take an interest in various forms of modelling, in a broad sense. This will cover mathematical models to role-play games and forum theatre, as well as the experimental economics (Janssen, Bousquet and Ostrom, 2011) and, of course, ABM. I also plan to continue developing Cormas to support its evolution in Pharo free community. Cormas will then become an intangible common good Cormas will then become a common intangible good that will nevertheless have to be further enhanced if it is to survive!

In parallel to my own research and experiments with development stakeholders, I want to continue sharing the values acquired from all these years of experience, but in addition to teaching modelling knowledge and techniques, I would like to share postures, such as animation postures in the field and listening postures for interdisciplinarity's sake.

References

- Alam, Shah Jamal, Frank Hillebrandt, et Michael Schillo. 2005. « Sociological implications of gift exchange in multiagent systems ». *Journal of Artificial Societies and Social Simulation* 8 (3). <http://jasss.soc.surrey.ac.uk/8/3/5.html>.
- Amblard, Frédéric, Pierre Bommel, et Juliette Rouchier. 2007. « Assessment and validation of multi-agent models ». In *Agent-based modelling and simulation in the social and human sciences*, Bardwell Press (GEMAS Studies in social analysis series), 93–116. Oxford: D. Phan, F. Amblard.
- Antona, Martine, et François Bousquet. 2017. *Une troisième voie entre l'État et le marché: Échanges avec Elinor Ostrom*. Quae.
- Arbeletche Favat, Pedro. 2016. « Análisis de la agricultura desde la perspectiva de la Economía Industrial: el caso de Uruguay ». Alicante, Espana: Universidad de Alicante. Departamento de Análisis Económico Aplicado. <http://hdl.handle.net/10045/54002>.
- Aubin, JP. 1991. *Viability Theory* Birkhäuser. Modern Birkhauser Classics. Boston: Springer.
- Axelrod, Robert. 2003. « Advancing the art of simulation in the social sciences ». *Japanese Journal for Management Information System. Special Issue on Agent-Based Modeling* 12 (3).
- Balci, Osman. 1998. « Verification, validation, and accreditation ». In , 1:41–48. IEEE Computer Society Press.
- Barnaud, Cécile, Patrick d'Aquino, William's Daré, et Raphaël Mathevet. 2017. « Dispositifs participatifs et asymétries de pouvoir: expliciter et interroger les positionnements ». *Participations*, no 16 (mai): 137–66.
- Barnaud, Cécile, Annemarie van Paassen, Guy Trébuil, Tanya Promburom, et François Bousquet. 2010. « Dealing with Power Games in a Companion Modelling Process: Lessons from Community Water Management in Thailand Highlands ». *The Journal of Agricultural Education and Extension* 16 (1): 55–74. <https://doi.org/10.1080/13892240903533152>.
- Barnaud, Cecile, et Annemarie Van Paassen. 2013. « Equity, Power Games, and Legitimacy: Dilemmas of Participatory Natural Resource Management ». *Ecology and Society* 18 (2). <https://doi.org/10.5751/ES-05459-180221>.
- Barreteau, Olivier. 2003. « The Joint Use of Role-Playing Games and Models Regarding Negotiation Processes: Characterization of Associations ». *Journal of Artificial Societies and Social Simulation* Vol. 6, No. 2. <<http://Jasss.Soc.Surrey.Ac.Uk/6/2/3.Html>>, 2003. <http://jasss.soc.surrey.ac.uk/6/2/3.html>.
- Barreteau, Olivier, et Francois Bousquet. 1999. « Jeux de rôles et validation de systèmes multi-agents. » In *actes des 7èmes JFIADSMA*, 99:67–80. La Réunion.
- Barreteau, Olivier, François Bousquet, et Jean-Marie Attonaty. 2001. « Role-playing games for opening the black box of multi-agent systems: method and lessons of its application to Senegal River Valley irrigated systems ». *Journal of artificial societies and social simulation* 4 (2): 5.
- Barreteau, Olivier, et others. 2003. « Our Companion Modelling Approach ». *Journal of Artificial*

Societies and Social Simulation Vol. 6, No. 1. <<http://Jasss.Soc.Surrey.Ac.Uk/6/2/1.Html>>, 2003. <http://jasss.soc.surrey.ac.uk/6/2/1.html>.

- Bart, Jonathan. 1995. « Acceptance criteria for using individual-based models to make management decisions ». *Ecological applications* 5 (2): 411–420.
- Becu, Nicolas, N Frascaria-Lacoste, et J Latune. 2014. « Distributed Asymmetric Simulation - Enhancing Participatory Simulation Using the Concept of Habitus. » In . Dornbirn, Austria, Bertelsmann.
- Berkes, Fikret, David Feeny, Bonnie J McCay, et James M Acheson. 1989. « The benefits of the commons ». *Nature* 340 (6229): 91.
- Bigbee, Anthony, Claudio Cioffi-Revilla, et Sean Luke. 2007. « Replication of Sugarscape using MASON ». In *Agent-Based Approaches in Economic and Social Complex Systems IV*, 183–190. Springer.
- Bommel, Pierre. 2009. « Définition d'un cadre méthodologique pour la conception de modèles multi-agents adaptée à la gestion des ressources renouvelables ». Montpellier, France: Université de Montpellier 2, France. <https://tel.archives-ouvertes.fr/tel-00396803/fr/>.
- Bommel, Pierre, Nicolas Bécu, Bruno Bonté, Etienne Delay, et Christophe Le Page. 2018. « Cormas in 10 years! » In . Virtual conference. <https://forum.comses.net/t/cormas-in-10-years>.
- Bommel, Pierre, Nicolas Bécu, Bruno Bonté, Etienne Delay, Christophe Le Page, Hernan Morales, Nick Papoulias, et Serge Stinckwich. 2018. « CORMAS, a participatory and interdisciplinary Agent Based Simulation Platform ». In . Università degli Studi di Cagliari – Sardinia.
- Bommel, Pierre, Nicolas Becu, Christophe Le Page, et François Bousquet. 2016. « Cormas: An Agent-Based Simulation Platform for Coupling Human Decisions with Computerized Dynamics ». In *Simulation and Gaming in the Network Society*, 9:387–410. Springer.
- Bommel, Pierre, Marie-Paule Bonnet, Emilie Coudel, Eva Haentjens, Cleber Nunes Kraus, Gustavo Melo, Stephanie Nasuti, et Christophe Le Page. 2016. « Livelihoods of Local Communities in an Amazonian Floodplain Coping with Global Changes. From Role-Playing Games to Hybrid Simulations to Involve Local Stakeholders in Participatory Foresight Study at Territorial Level ». *Communication avec actes. Proceedings of the 8th International Congress on Environmental Modelling and Software*. 2016. <http://www.iemss.org/sites/iemss2016/vol4.php>.
- Bommel, Pierre, Francisco Dieguez, Danilo Bartaburu, Emilio Duarte, Esteban Montes, Marcelo Pereira Machin, Jorge Corral, Carlos José Pereira de Lucena, et Hermes Morales Grosskopf. 2014. « A Further Step Towards Participatory Modelling. Fostering Stakeholder Involvement in Designing Models by Using Executable UML ». *Journal of Artificial Societies and Social Simulation* 17 (1): 6.
- Bommel, Pierre, Thérèse Libourel, et Sylvie Lardon. 2000. « Conception objet dans le cadre des systèmes d'information spatiaux: Agrégation spatiale et généralisation. » In *INFORSID*, 302–313.
- Bommel, Pierre, et Jean Pierre Müller. 2007. « An Introduction to UML for Modelling in the Human and Social Sciences ». In *Agent-Based Modelling and Simulation in the Social and Human Sciences*, Bardwell Press, 273–294. GEMAS Studies in Social Analysis Series. Oxford: D. Phan, F. Amblard.

- Bommel, Pierre, Rene Pocard-Chapuis, Amaury Burlamaqui Bendahan, et Emilie Coudel. 2012. « An ABM to monitor landscape dynamics and to undertake collective foresight investigations in the Amazon ». In *Proceedings of the 2012 Third Brazilian Workshop on Social Simulation*, 91–98. IEEE Computer Society.
- Boudon, Raymond, et Renaud Fillieule. 2012. « L'individualisme méthodologique ». In *Que sais-je ?*, 13e éd.:41–91. Paris cedex 14: Presses Universitaires de France. <https://www.cairn.info/les-methodes-en-sociologie--9782130606338-p-41.htm>.
- Bourdieu, Pierre. 1980. *Le Sens pratique*. Éditions de Minuit. Paris.
- Bousquet, François. 2005. *Companion Modeling and Multi-Agent Systems for Integrated Natural Resource Management in Asia*. Int. Rice Res. Inst.
- Bousquet, François, Martine Antona, et Jacques Weber. 1994. « Simulations multi-agents et gestion des ressources renouvelables ». In *CIRAD-SAR*.
- Bousquet, François, Innocent Bakam, Hubert Proton, et Christophe Le Page. 1998. « Cormas: Common-pool resources and multi-agent systems ». In *Tasks and Methods in Applied Artificial Intelligence*, édité par Angel Pasqual del Pobil, José Mira, et Moonis Ali, 1416:826–37. Berlin, Heidelberg: Springer Berlin Heidelberg. http://link.springer.com/10.1007/3-540-64574-8_469.
- Boussard, Jean-Marc, Françoise Gérard, et Marie-Gabrielle Piketty. 2005. *Libéraliser l'agriculture mondiale?: théories, modèles et réalités*. Editions Quae.
- Bradbury, Roger. 2002. « Futures, predictions and other foolishness ». *Complexity and Ecosystem Management*. Edward Elgar, Cheltenham UK, 48–62.
- Brant, John, et Ralph E Johnson. 1994. « Creating Tools in HotDraw by Composition. » In *Citeseer*.
- Brauer, Johannes. 2015. « The VisualWorks Development Environment ». In *Programming Smalltalk – Object-Orientation from the Beginning*, 77–96. Springer Fachmedien Wiesbaden. http://link.springer.com/chapter/10.1007/978-3-658-06823-3_5.
- [Collectif ComMod] Bousquet, F, M Antona, S Aubert, C Barnaud, O Barreteau, N Becu, S Boisseau, et al. 2009. « La posture d'accompagnement des processus de prise de décision: les références et les questions transdisciplinaires ». In *Modélisation de l'environnement: entre natures et sociétés.*, 71–89. Quae. Hervé Dominique (ed.), Laloë Francis (ed.).
- ComMod, Collectif. 2005. « La modélisation comme outil d'accompagnement ». *Natures Sciences Sociétés* 13 (2): 165–68. <https://doi.org/10.1051/nss:2005023>.
- Conte, Rosaria, et Cristiano Castelfranchi. 1995. « Understanding the functions of norms in social groups through simulation ». *Artificial societies: the computer simulation of social life* 1: 252–67.
- Corral, J, P Arbeletche, JC Burges, H Morales, G Continanza, J Couderc, V Courdin, et P Bommel. 2008. « Multi-Agent Systems applied to land use and social changes in Rio de la Plata basin (South America) ». 8th European International Farming Systems Association, France.
- Crookall, David, Allan Martin, Danny Saunders, et Alan Coote. 1986. « Human and computer involvement in simulation ». *Simulation & Games* 17 (3): 345–75.

- Damasio, Antonio. 1999. *The Feeling of what Happens: Body and Emotion in the Making of Consciousness*. Houghton Mifflin Harcourt.
- D'Aquino, Patrick, Christophe Le Page, Francois Bousquet, et Alassane Bah. 2003. « Using Self-Designed Role-Playing Games and a Multi-Agent System to Empower a Local Decision-Making Process for Land Use Management: The SelfCormas Experiment in Senegal ». *Journal of Artificial Societies and Social Simulation* 6 (3). <http://jasss.soc.surrey.ac.uk/6/3/5.html>.
- Daré, William, Sigrid Aubert, Alassane Bah, Aurélie Botta, Ibrahima Diop-Gaye, Christine Fourage, Gilles Lajoie, et Grégoire Leclerc. 2008. « Difficultés de la participation en recherche-action: retour d'expériences de modélisation d'accompagnement en appui à l'aménagement du territoire au Sénégal et à la Réunion ». [Vertigo] *La revue électronique en sciences de l'environnement* 8 (2).
- Daré, William's, Cécile Barnaud, Patrick d'Aquino, Michel Étienne, Christine Fourage, et Véronique Souchère. 2010. « La posture du comédien: un savoir être, des savoir-faire ». In *Modélisation d'accompagnement*, 47-70. Update Sciences & Technologies. Versailles: Editions Quæ. <https://doi.org/10.3917/quae.etien.2010.01.0009>.
- Deffuant, Guillaume, Scott Moss, et Wander Jager. 2006. « Dialogues concerning a (possibly) new science ». *Journal of Artificial Societies and Social Simulation* 9 (1). <http://jasss.soc.surrey.ac.uk/9/1/1.html>.
- Deffuant, Guillaume, Gérard Weisbuch, Frédéric Amblard, et Thierry Faure. 2003. « Simple is beautiful... and necessary ». *Journal of Artificial Societies and Social Simulation* 6 (1): 6.
- Descombes, Vincent. 1996. *Les institutions du sens*. Les éditions de minuit.
- Dieguez Cameroni, FJ, R Terra, S Tabarez, Pierre Bommel, Jorge Corral, Danilo Bartaburu, Marcelo Pereira, et al. 2014. « Virtual experiments using a participatory model to explore interactions between climatic variability and management decisions in extensive grazing systems in the basaltic region of Uruguay ». *Agricultural Systems* 130 (C): 89-104.
- Drogoul, Alexis, Diane Vanbergue, et Thomas Meurisse. 2003. « Simulation Orientée Agent: où sont les agents ». In *Actes des Journées de Rochebrune, Rencontres interdisciplinaires sur les systèmes complexes naturels et artificiels*.
- Ducasse, Stéphane. 1997. « Des techniques de contrôle de l'envoi de messages en Smalltalk ». *Revue des Sciences et Technologies de l'Information (RSTI) — L'Objet*, 3, 1997, Hermes édition.
- Durand, Marie-Hélène, et Martine Antona. 2013. « Le très long terme: prévoir, c'est gouverner ». In *Rendre possible: Jacques Weber, itinéraire d'un économiste passe-frontières*. Quæ, 181-90.
- Durkheim, Emile. 1897. *Le Suicide, étude de sociologie*. Paris: Felix Alcan.
- Elias, Norbert. 1991. *La société des individus. 1940-1950*. Paris: Fayard.
- Epstein, Joshua M, et Robert Axtell. 1996. *Growing artificial societies: social science from the bottom up*. Brookings Institution Press.
- Erasmus, L, AS Van Jaarsveld, et Pierre Bommel. 2002. « A spatially explicit modelling approach to socio-economic development in South Africa ». In *Proceedings of the International Environmental Modelling and Software Society Conference*, 91-96. Lugano, Switzerland: Eds A.E. Rizzoli, A.J. Jakeman.

- Erceau, Jean. 1995. « Complexité et conception des systèmes complexes, vers une ingénierie des systèmes complexes ». Séminaire sur la complexité du CP2i 13.
- Étienne, Michel. 2010. La modélisation d'accompagnement: une démarche participative en appui au développement durable. Update Sciences & Technologies. Versailles, France: Editions Quae.
- Étienne, Michel, éd. 2011. Companion Modelling. A Participatory Approach to Support Sustainable Development. Dordrecht: Springer Netherlands. <http://link.springer.com/10.1007/978-94-017-8557-0>.
- Farolfi, S, C Le Page, P Bommel, et L Erasmus. 2003. « Evaluating policy options for management of livestock effluents in the Reunion Island using a multi-agent system ». In 25th International Conference of Agricultural Economists, 21. Durban, South Africa. 16-22 August 2003.
- Ferber, Jacques. 1995. Les Systèmes multi-agents: Vers une intelligence collective. InterEditions.
- Ferber, Jacques. 2006. « Concepts et méthodologies multi-agents. » In Modélisation et simulation multi-agents pour les Sciences de l'Homme et de la Société, Hermes Science Publications. Paris, France: Amblard F., Phan D.
- Ferber, Jacques. 2007. « Multi-Agent Concepts and Methodologies ». In Agent-Based Modelling and Simulation in the Social and Human Sciences, Bardwell Press. Oxford: D. Phan and F. Amblard.
- Ferber, Jacques, et Véronique Guérin. 2003. « Représentations et simulation: de la modélisation à la mise en situation ». Le statut épistémologique de la simulation, 85-98.
- Ferber, Jacques, et Jean-Pierre Müller. 1996. « Influences and reaction: a model of situated multiagent systems ». In , 72-79.
- Friedman, Milton. 1981. Market Mechanisms and Central Economic Planning. American Enterprise Institute for Public Policy Research Washington, DC.
- Georges, Fanny. 2012. « Avatars et identité ». Hermès, La Revue 62 (1): 33-40.
- Grimm, Volker. 1999. « Ten years of individual-based modelling in ecology: what have we learned and what could we learn in the future? » Ecological Modelling 115 (2): 129-48. [https://doi.org/10.1016/S0304-3800\(98\)00188-4](https://doi.org/10.1016/S0304-3800(98)00188-4).
- Gurung, Tayan Raj, Francois Bousquet, et Guy Trébuil. 2006. « Companion modeling, conflict resolution, and institution building: sharing irrigation water in the Lingmuteychu Watershed, Bhutan ». Ecology and Society 11(2): 36, 2006.
- Guyot, Paul. 2006. « Simulations multi-agents participatives: Faire interagir agents et humains pour explorer, modéliser et reproduire les comportements collectifs. Modélisation et simulation ». Université Pierre et Marie Curie - Paris VI. HAL [tel-00084064](https://hal.archives-ouvertes.fr/hal-00084064).
- Hales, David, Juliette Rouchier, et Bruce Edmonds. 2003. « Model-to-model analysis ». Journal of Artificial Societies and Social Simulation 6 (4).
- Hardin, Garrett. 1968. « The Tragedy of the Commons ». Science 162 (3859): 1243-48. <https://doi.org/10.1126/science.162.3859.1243>.
- Hayek, Friedrich. 1966. « Lecture on a Master Mind: Dr Bernard Mandeville ».
- Holland, John Henry. 1995. Hidden orderhow adaptation builds complexity.

- Horlitz, Thomas. 2007. « The Role of Model Interfaces for Participation in Water Management ». *Water Resources Management* 21 (7): 1091–1102. <https://doi.org/10.1007/s11269-006-9100-9>.
- Janssen, Marco A., François Bousquet, et Elinor Ostrom. 2011. « A multimethod approach to study the governance of social-ecological systems ». *Natures Sciences Sociétés* 19 (4): 382–394.
- Janssen, Marco A., et Elinor Ostrom. 2006. « Empirically based, agent-based models ». *Ecology and Society* 11 (2): 37.
- Jensen, Pablo. 2015. « Les simulations multi-agents, une nouvelle approche du social?. À propos de: Gianluca Manzo (dir.), «La simulation multi-agents: principes et applications aux phénomènes sociaux», Revue française de sociologie, n° 55-4, octobre-décembre 2014. » *Lectures, Review Essays*. <http://journals.openedition.org/lectures/18393>.
- Lardon, S, C Baron, P Bommel, F Bousquet, C Le Page, R Lifran, P Monestiez, et P Reitz. 1998. « Modéliser les configurations et les stratégies spatiales dans un système multi-agents pour la maîtrise de dynamiques d'embroussaillage ». In *Modeles et systemes multi-agents pour la gestion de l'environnement et des territoires*, 5-8 Oct 1998, 169–185. Clermont-Ferrand, France.
- Lardon, Sylvie, Pierre Bommel, François Bousquet, Christophe Le Page, Thérèse Libourel, Robert Lifran, et Pierre-Louis Osty. 2000. « De la simulation de l'embroussaillage à un outil d'aide à la gestion de l'espace - un modèle de transformations de l'espace. » In *Systèmes multi-agents : Méthodologie, technologie et expériences - JFIADSM 00 - huitième journées francophones d'Intelligence Artificielle et systèmes multi-agents*, Saint-Jean-la-Vêtre, Loire, France, October 2-4, 2000, 357–374.
- Lawson, Barry G, et Steve Park. 2000. « Asynchronous time evolution in an artificial society mode ». *Journal of Artificial Societies and Social Simulation* 3 (1).
- Le Fur, J, et P Bommel. 1998. « Couplage d'un modèle multi-agent de la dynamique d'une ressource marine avec un modèle multi-agent de l'exploitation halieutique artisanale sénégalaise ». *Séminaire SMAS, INRA Montpellier*.
- Le Moigne, JL. 1977. « La Théorie du Système Général: Théorie de la Modélisation: Presses Universitaires de France ». Paris, France.
- Le Page, Christophe. 2017. « Simulation multi-agent interactive: engager des populations locales dans la modélisation des socio-écosystèmes pour stimuler l'apprentissage social ». *Habilitation à Diriger des Recherches, Université Pierre et Marie Curie, Paris, France*.
- Le Page, Christophe, Géraldine Abrami, Olivier Barreteau, Nicolas Becu, Pierre Bommel, Aurélie Botta, Anne Dray, Claude Monteil, et Véronique Souchère. 2010. « Des modèles pour partager des représentations ». In *Modélisation d'accompagnement: une démarche participative en appui au développement durable*, Quae, 71–101. Versailles, France: M. Etienne.
- Le Page, Christophe, Géraldine Abrami, Olivier Barreteau, Nicolas Becu, Pierre Bommel, Aurélie Botta, Anne Dray, Claude Monteil, et Véronique Souchère. 2014. « Models for sharing representations ». In *Companion modelling*, 69–101. Springer Netherlands.
- Le Page, Christophe, Géraldine Abrami, Nicolas Becu, Pierre Bommel, Bruno Bonte, François Bousquet, Benoit Gaudou, Jean Pierre Müller, Damien Philippon, et Patrick Taillandier. 2017.

- « Lessons from implementing in parallel with 3 platforms the same didactic agent-based model ». In CoMSES Net virtual conference « CoMSES 2017 ». <https://forum.comses.net/t/session-on-model-reuse/89>.
- Le Page, Christophe, et Olivier Barreteau. 2013. « Quelques élucubrations sur Jacques Weber et la modélisation ». In *Rendre possible : Jacques Weber, itinéraire d'un économiste passe-frontières*, Quae. Indisciplines. Versailles: M. Bouamrane, M. Antona, R. Barbault, M.C. Cormier-Salem.
- Le Page, Christophe, Nicolas Becu, Pierre Bommel, et Francois Bousquet. 2010. « Participatory Agent-Based Simulation for Renewable Resource Management: The Role of the Cormas Simulation Platform to Nurture a Community of Practice ». *Journal of Artificial Societies and Social Simulation* 15 (1): 10.
- Le Page, Christophe, Sylvie Lardon, Pierre Bommel, Christian Baron, et François Bousquet. 1999. « Entités spatiales génériques et modèles de simulation multi-agent ». In *JFIADSMA'99*. Vol. Saint-Gilles, La réunion. 8-10 novembre 1999: Hermès.
- Le Page, Christophe, et Arthur Perrotton. 2017. « KILT: A Modelling Approach Based on Participatory Agent-Based Simulation of Stylized Socio-Ecosystems to Stimulate Social Learning with Local Stakeholders ». In , 31-44. Springer International Publishing. São Paulo, Brazil: Sukthankar G., Rodriguez-Aguilar J. A. https://doi.org/10.1007/978-3-319-71679-4_3.
- Livet, Pierre, Denis Phan, et Lena Sanders. 2014. « Diversité et complémentarité des modèles multi-agents en sciences sociales ». *Revue française de sociologie* 55 (4): 689-729. <https://doi.org/10.3917/rfs.554.0689>.
- Locher, Fabien. 2013. « Les pâturages de la Guerre froide : Garrett Hardin et la “Tragédie des communs” ». *Revue d'histoire moderne & contemporaine* 60(1) (1): 7-36. <https://doi.org/10.3917/rhmc.601.0007>.
- Magni-Berton, Raül. 2008. « Holisme durkheimien et holisme bourdieusien. Étude sur la polysémie d'un mot ». *L'Année sociologique* 58 (2): 299-318. <https://doi.org/10.3917/anso.082.0299>.
- Manzo, Gianluca. 2007. « Progrès et “urgence” de la modélisation en sociologie. du concept de “modèle générateur” et de sa mise en œuvre ». *L'Année sociologique* 57 (1): 13-61. <https://doi.org/10.3917/anso.071.0013>.
- Manzo, Gianluca. 2014a. « La simulation multi-agents : principes et applications aux phénomènes sociaux ». 55-4, 2014, Les Presses de Sciences Po édition.
- Manzo, Gianluca. 2014b. « Potentialités et limites de la simulation multi-agents : une introduction ». *Revue française de sociologie* 55 (4): 653-88. <https://doi.org/10.3917/rfs.554.0653>.
- Maturana, Humberto R, et Francisco J Varela. 1994. *L'arbre de la connaissance*. Ed. Addison-Wesley France.
- Meadows, D, et D Meadows. 1993. « Fish Banks news, Fish Banks limited and Laboratory for Interactive Learning ». University of New Hampshire: Durham, NH, USA.
- Meadows, Denis, Donella Meadows, Jørgen Randers, et William Behrens. 1972. « The Limits to Growth ». Club of Rome. New York: Universe Books.
- Mellor, Stephen J., et Marc Balcer. 2002. *Executable UML: A Foundation for Model-Driven*

- Architectures. Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc.
- Melo, Gustavo, Emilie Coudel, et Pierre Bommel. 2014. « What futures for the Amazonian floodplains? A participatory prospective approach of a biodiversity hotspot under economic and climate change ».
- Meurisse, Thomas. 2004. « Simulation multi-agent: du modèle à l'opérationnalisation ». Thèse de Doctorat, Université de Paris 6.
- Michel, Fabien. 2004. « Formalisme, outils et éléments méthodologiques pour la modélisation et la simulation multi-agents ». Montpellier II, , sciences et techniques du Languedoc.
- Michel, Fabien, Pierre Bommel, et Jacques Ferber. 2002. « Simulation distribuée interactive sous MadKit. » In JFSMA, 175–178.
- Michel, Fabien, Abdelkader Gouaich, et Jacques Ferber. 2003. « Weak interaction and strong interaction in agent based simulations ». In , 43–56. Springer.
- Morales Grosskopf, Hermes Morales, Pedro Arbeleche, Pierre Bommel, Julio Cesar Burges, Marcelo Champredonde, Jorge Corral, Jean Francois Tourrand, et others. 2010. « Modeling rangeland management change in Uruguay. » Cahiers Agricultures 19 (2): 112–117. <https://doi.org/10.1684/agr.2010.0385>.
- Morand, Bernard. 2000. « Le diagramme : à la périphérie ou au cœur de la cognition ? » In Rencontres interdisciplinaires sur les représentations graphiques dans les systèmes complexes naturels et artificiels. Rochebrune, France.
- Mullon, Christian. 2005. « Vers un usage concerté de la modélisation et de la simulation dans les recherches interdisciplinaires ». Natures Sciences Sociétés 13 (2): 172–173.
- Neumann, Martin. 2013. « Social Constraint ». In *Simulating Social Complexity: A Handbook*, édité par Bruce Edmonds et Ruth Meyer, 335–364. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-93813-2_14.
- OMG. 2008. « Model Driven Architecture, MDA Guide Version 1.0.1 ».
- OMG. 2017. « Unified Modeling Language Specification v2.5.1 ». <http://www.omg.org/spec/UML/2.0/>.
- Orléan, André. 2004. « What is a collective belief? » In *Cognitive economics*, 199–212. Berlin, Heidelberg: Springer.
- Ostrom, Elinor. 2015. *Governing the commons*. Cambridge university press.
- Pepper J.W., et Smuts B.B. 2000. « The evolution of cooperation in an ecological context: an agent-based model ». *Dynamics of human and primate societies: agent-based modeling of social and spatial processes*, 2000, Oxford University Press édition, sect. T.A. Kohler and G.J. Gumerman, eds.
- Petitjean, Olivier. 2010. « Les biens communs, modèle de gestion des ressources naturelles ». Passerelle dph no 02, Ritimo, Paris.
- Rykiel Jr, Edward J. 1996. « Testing ecological models: the meaning of validation ». *Ecological modelling* 90 (3): 229–244.
- Saltelli, Andrea, Stefano Tarantola, et Francesca Campolongo. 2000. « Sensitivity analysis as an

- ingredient of modeling ». *Statistical Science* 15 (4): 377-395.
- Schaefer, Milner B. 1954. « Some Considerations of Population Dynamics and Economics in Relation to the Management of the Commercial Marine Fisheries ». *Journal of the Fisheries Research Board of Canada* 14 (5): 669-681. <https://doi.org/10.1139/f57-025>.
- Squazzoni, Flaminio, et Niccolò Casnici. 2013. « Is Social Simulation a Social Science Outstation? A Bibliometric Analysis of the Impact of JASSS ». *Journal of Artificial Societies and Social Simulation* 16 (1): 10. <https://doi.org/10.18564/jasss.2192>.
- Uhnak, Peter, et Pierre Bommel. 2016. « Facilitating the design of ABM and the code generation to promote participatory modelling ». In *Proceedings of the 8th International Congress on Environmental Modelling and Software*, 827-835. Toulouse, France. July 10-14: Sauvage, S., Sánchez-Pérez, J.M., Rizzoli, A.E.
- Uhnák, Peter, et Robert Pergl. 2016. « The OpenPonk modeling platform. » In *Proceedings of the 11th edition of the International Workshop on Smalltalk Technologies*, 14. ACM.
- Venturini, Tommaso, Pablo Jensen, et Bruno Latour. 2015. « Fill in the Gap: A New Alliance for Social and Natural Sciences ». *Journal of Artificial Societies and Social Simulation* 18 (2): 11. <https://doi.org/10.18564/jasss.2729>.
- Voinov, Alexey, et Francois Bousquet. 2010. « Modelling with stakeholders ». *Environmental Modelling & Software, Thematic Issue - Modelling with Stakeholders*, 25 (11): 1268-1281. <https://doi.org/10.1016/j.envsoft.2010.03.007>.
- Weber, Jacques. 1995. « Gestion des ressources renouvelables: fondements théoriques d'un programme de recherche ». In *Rendre possible*, 35-52. Editions Quæ.
- Weber, Jacques, et Denis Bailly. 1993. « Prévoir, c'est gouverner ». *Natures Sciences Sociétés* 1 (1): 59-64.
- Weber, Jacques, Jean-Marie Betsch, et Philippe Cury. 1990. « A l'interface hommes-nature: les ressources renouvelables ». In *Colloque National Recherche et Environnement*, 39-50. CNRS Programme Environnement.
- Weber, Jacques, et Jean-Pierre Revéret. 1993. « Biens communs: les leures de la privatisation ». *Le monde diplomatique*, no 2: 71-73.
- Zeigler, Bernard P., Herbert Praehofer, et Tag Gon Kim. 2000. *Theory of Modeling and Simulation: Integrating Discrete Event and Continuous Complex Dynamic Systems*. Academic Press.