Ecosystem complexity described with ontological tool for a multi-scale, multi-model approaches in distributed environment

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ABSTRACT

Aquatic ecosystems are natural complex systems. They are the site of a great number of phenomena. Thus, many studies model each of these phenomena, using law-based approach (most of the time differential equations) or rule-based approach (individual-based models in particular). Owing to their complex nature, aquatic ecosystems are hard to study and resist a reductionist approach. We based our model on the holarchic (non directional hierarchic) nature of the ecosystems. First, aquatic ecosystems are crossed by structuring fluxes (light radiation, mass transport, etc.) which are mainly conveyed by fluid flow. So, we propose to model these fluid flows with a multi-scale simulation detecting emergent formation and managing them on different scales. Second, a part of aquatic ecosystems are species organizations called food chain. These ones are themselves interacting complex subsystems with multi non-directional retroactions between them and their environment. These retroactions can be modeled at different levels. Thus, we propose an hybrid holarchic compartmental model. This one aims at easing the gathering of phenomenon in a multi-model, multi-level simulation for studying food chain. We finally present a fluid-flow simulation and a food chain simulation using the proposed models.

1 Ecosystems as complex multi-scale systems

The botanist Tansley (Tansley, 1935) defines ecosystems as ”The more fundamental conception is ... the whole system (in the sense of physics) including not only the organism-complex but also the whole complex of physical factors forming what we call the environment. We cannot separate them (the organisms) from their special environment with which they form one physical system ... It is the system so formed which [provides] the basic units of nature on the face of the earth ... These ecosystems, as we may call them, are of the most various kind and sizes.”

Typically, ecosystems are described as a biotope and a biocenisis in mutual interaction. Moreover, they are crossed by fluxes (mass tranport or energy) which dynamically structure them. A reductionist approach fails in modeling such mutual interactions and feed-back processes. New approaches based on general system theory concepts have therefore been tried to produce more efficient models.

Ecosystems throw general system theory concepts

Ecosystems are systems as described in the general system theory (Le Moigne, 1994) and can be seen as a set of interacting elements which are characterized by following aspects:

- **mutual dependence.** Each element is directly linked with other elements in structure or dynamic. Therefore, its evolution depends on the other elements in interaction with it. Finally, separating an element from its neighborhood modifies it.
- **emergence of organizations.** The interaction of elements leads to the emergence of natural organizations which generate “new entities”. Those entities differ from their components in their structure and dynamic.
- **feed-back processes.** This is the retroaction from the natural organizations to its own components.

Emergence processes act recursively and generate hierarchical systems organization. An adapted description is the one called SOHOS according to Koestler (Koestler and Smythies, 1969). SOHOS stands for Self-Organized Holarchic Open Systems. An holarchy is a non-directional hierarchy in which the members are called holon.

If we consider the three previous characteristic aspects of ecosystems, an adapted definition of ecosystems could be:

"biotope+biocenosis", natural multi-level holarchic systems, crossed by structuring fluxes.

Ecosystems as holarchic systems, must be studied at many levels of time and space (each level is significant) and are crossed by fluxes. Many tools exist to model and simulate ecosystems. Those tools differ by the nature of the model they use, the level they describe and the phenomena they directly take into account. Thus, they mainly focus on one aspect of the ecosystem. Therefore, gathering all these models is a hard task due to structural differences between these tools. Mixing these models is seldom theoretically feasible, and when it is, the computation of the resulting simulation is often crippled by a terrible computation time.Unfortunately, raising the number of interactions modeled is the concern of most modelers. We aim at providing a model which would facilitate the gathering of models for simulating aquatic ecosystems in a multi-scale description.

Law-based models vs. Rule-based models

We give in the following part, a possible classification by considering two main categories of models: law-based and rule-based ones. Then, we explain why we finally proposed a mixed model.

Law-based models are the most classical models in sciences. Koyré defines a law as "what does not change when everything does". In fact, law-based models are often continuous in space and time and rely upon mathematical tools, mostly differential equations and analytical models. The level of description is always global with global variables on which we apply the equations of the model. For example, in ecology, population models using exponential or logarithmic equations are law-based.

Another approach uses rule-based models. This class of models doesn't sum up a global behavior of the phenomenon in a few equations. With this approach, some entities and their behaviour are described by a set of rules. Well-known models of this class are systems of formal deduction and compilers. These models are also used in simulation. In this context, to apprehend the whole trajectory of the global behavior, we have to compute all the concurrent rules concerning a set of constitutive entities of the phenomenon. The level of description is in this case local, so that spacial aspects of the model can be considered. Finally, rule-based models naturally take into account local variation and adapt to those changes. This approach is so well adapted with computing simulation and less adapted to analytic resolution as law-based could be. The rule-based models have been popularized with game theories and are now frequently used in biology or social sciences. With improvement of computer technologies, ecology founds efficient models in such approaches and developped more recently Individual-Based Models (IBM) (DeAngelis and Gross, 1992a) (Grim, 1999) which can be classified as Rule-based models.

Mixed models for ecological purposes

Both types of models are very useful in ecology depending on what phenomena and environments are represented. Moreover, they present particular features making them complementary.

- Global events occurring with little variability due to environmental changes are precisely modeled with law-based model. The discretization of rule-based model should induce a loss of information when applied to those phenomena.
- Environmental dependent events and especially spacial ones are poorly modeled with law-based methods. By nature, rule-based models cope with the local and environmental variations.

In IBM, individuals are represented (Haefner, 1992) as a set of i-state (individual state or values). Moreover, in law-based models, global variables are used and could be seen as environmental states (e-state). Therefore, an ecosystem could be globally described as a set of e-states. Most of the time, IBMs use those variables to modify their own states according to their rules. That way, we unify the two kinds of models with a single representation. Finally, some law-based models don't consider e-states but p-states (for population state). Thus, they model some features of a population on a global level. The global state is a linear combination of its own individual states. Therefore, we consider each element of our model as a set of states (e-states, i-states or p-states).

Changing the scale: means and goals

Ecosystems are multi-scale by nature and links (or interactions) between those scales are as important as what they contain (individuals for example). Thus, when studying an ecosystem, one should choose many levels of description, define the interactions between those levels and ideally redefine the scales during the simulation.

On the one hand, multi-scale models give solutions to manage the great number of elements which are low-level entities of the ecosystem. Making a simulation gathering enough elements to be significant become a hard task. Finding organizations which sum up many entities in a high level of description allows for realistic simulations.

On the other hand, multi-scale model gives pertinent informations to describe systems in term of general system theory. As we described before, organizations emerge from the interaction between the entities of the systems. The structures, behaviors, relations of those systems differ from their constitutive element. Most of the time, they are relevant on a different scale. Taking into account this new description level gives precious informations to understand the ecosystem as a complex system and to represent it in its whole in the simulation. In this scale description, they can retro-act on their constitutive components.

Rule-based models allow many ways to change the scale, depending of the tools used to define the rules. It is frequent that individual-based simulations contain two levels of description and define rules to compose system and decompose it into elements if necessary.

2 Multi-scale model for fluid flow simulation

Fluid mechanic model and its structures

Hydrodynamics usually deal with scales where fluids can be considered continous. The set of laws describing continuous fluid behavior is called Navier-Stokes equation. These equations are non-linear differential equations.

The problem is, Navier-Stokes equations generally can't be solved analytically. Numeric solutions are then to be found.

Amongst the set of schemes aiming at discretizing then numerically simulate fluid flows, we chose the approach called vortex methods (Leonard, 1980).

In vortex methods, the flow is separated in a number of abstract particles, each being a local descriptor of the flow. These particles indicate the speed, vorticity etc. of the flow where they are located.

These particles are not fixed: the fluid they describe conveys them. They can in fact be seen as mobile interpolation points, from whom the cinematic charateristics of the fluid can be computed anywhere.

This model is of interest to us as it is a local model, hence better able to deal with local heterogeneities. The values of the particles are computed through the interactions between the particles, most notably through Biot-Savart formula. More details on this computation can be found in (Bertelle et al., 2002).

The vortex method we use is of $O(n^2)$ complexity. Finding ways of lightening this calculus is therefore important. One lead is through making our model multi-scale, and only computing entities at the scale we need them. This is our second motivation for our using different levels of description.

In order to have different levels of description, we will have to use an adapted description of the simulation entities.

These entities come and go during the simulation, and thus we need a method to change the level of their description *during* the simulation, and not beforehand the way it is usually done.

In our fluid flow, the main entities as we explained are vortexes. Not only do we therefore need to detect emerging vortexes by monitoring lower level vortexes particles, but also, as these vortexes aggregate among themselves to form even bigger vortexes, make this detection process iterative.

Detecting the structures is not enough: we also need to create them in the simulation once they are detected. We must make these new entities live in the simulation, interacting with its various inhabitants (most notably particles, vortexes). They must evolve, whether it is growing or decaying to its possible disintegration.

Detecting emergent vortexes among the vortex particles

Structures are detected as clusters of particles sharing some properties. For vortexes these properties are spatial coordinates and rotation sense.

As described in the figure 1, the process is:

- Delaunay triangulation of the particles
- Computation of a minimal spanning tree of this triangulation
- Edges that are too much longer than the average length of edges leading to the particles are removed. So are edges linking particles of opposite rotational.
- The convex hull of the remaining trees is computed
- An ellipse approximates the hull through a least square method

Further details on this process can be found in (Tranouez et al., 2001).

Scale transfer : making simulation entities of the detected structures

Detected structures are created in the simulation where they take the place of the particles whose interactions gave them birth.

The vortex structures are implemented through multiplicity automata (Bertelle et al., 2002). These automata handle both the relations between higher-level vortexes and the relations between them and the basic particles.

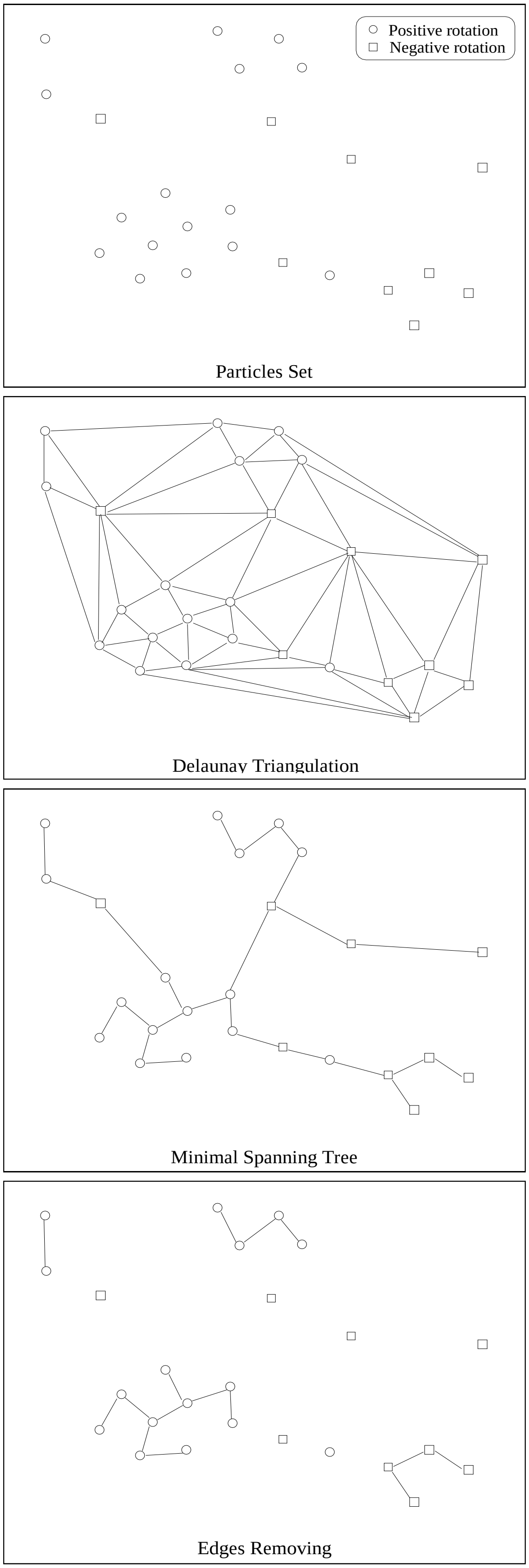

Figure 1: Successive sub-steps for clusters formation

The relations between vortexes and their environment are handled through a method based on the eco-resolution model (Drogoul and Dubreuil, 1992), in which entities are described through a perception and combat metaphor. The associated perceptions and actions are:

- Perceiving an intruder means being on a collision course with another vortex. Figure 2 sums up the various possibilities of interception by vortexes of opposed rotation and how each is translated in a perception.
- Attacking another vortex means sending it a message.
- Being attacked means receiving such a message.
- Fleeing means being destabilized: the vortex structure shrinks and creates particles on its border (see Figure3). Too much flight can lead to the death of the structure, which is then decomposed in its basic particles.
- Getting satisfaction means aggregating surrounding particles of compatible vorticity. This calculation is done through a method close to the initial structure detection : Delaunay triangulation, spanning tree, removal of edges. Compacity criteria are then used to estimate whether the tree should be added to the vortex and thus a new ellipse be computed or not. For instance in figure 4, the particles on the lower left will be aggregated while those on top won't.

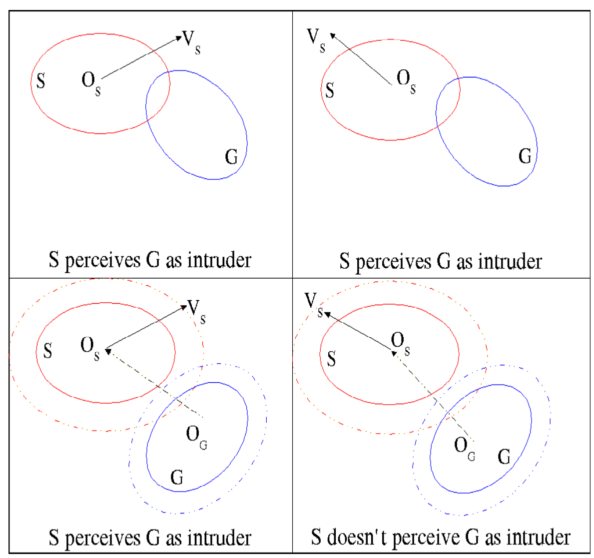

Figure 2: Intruders perceptions

The described process is then iterated. New structures are detected and implemented, while others grow, shrink or disappear altogether.

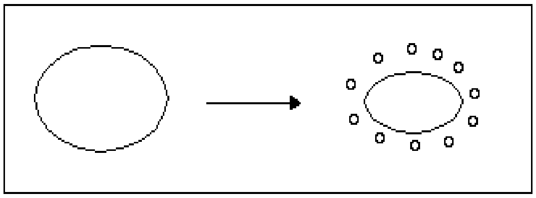

Figure 3: Structure flight as reducing its dimension

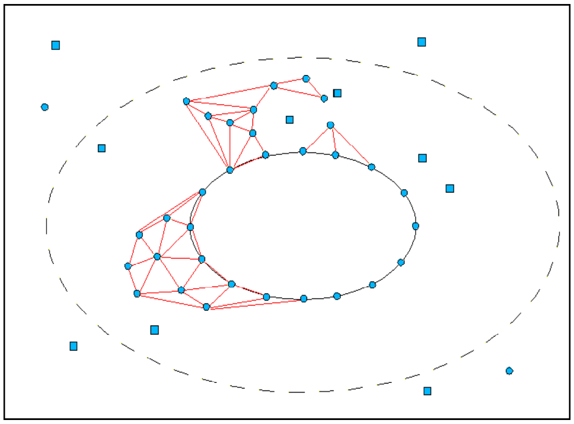

Figure 4: Aggregation from structure in satisfaction process

3 An holarchic hybrid model for modeling ecosystems

Main concepts

First, let's start with a description of an ecosystem life cycle. An ecosystem always go through three states characterized by its biotope and its inner complexity.

- To begin with, the profile of an ecosystem can be described as juvenile. The ecosystem itself contains many raw materials and its biodiversity is low. The biotope is mainly made of simple organisms. Those organisms modify the layout as they keep on multiplying and consuming the raw material. The environmental condition has little influence on their development. The main factor limiting their growth in size and number is the quantity of material and space.

- Then, an ecosystem evolves into a mature or adult form. An adult ecosystem undergoes a replacement of its original settlement (simple organisms) with complex organisms. Those organisms suit the ecosystem characteristics and tend to maintain them. They consume and produce (or participate to the production of) raw materials. Those organisms replace the simple organisms (but some simple organisms remain). So on, the biodiversity of the ecosystem is very high. We should be aware that the complex organisms need the building made by the simple organisms during the juvenile stage to appear.

- Finally, an ecosystem tends to be aging. When being adult, the ecosystem is made of many types of complex systems, each one participating to the maintenance of the system. As it grows old, the ecosystem tends to lower his complexity and biodiversity by eliminating the less performant complex organisms and conserving the best association of organisms.

During its life, an ecosystem always undergoes stress period making it pass from one step to another (sometimes regressing as it is the case when an ecosystem is being exploited). We point out that biotope and biocenosis are directly linked and that each organism acts for his ecosystem as the same time as it is influenced by it.

Following this line of thought, we adopt a well-known description of the biotope based on a classification of the organisms. That classification is made of three parts:

1. **Producers.** Producers are the base of the ecosystem. They are responsible for the production of organic mass by consuming inorganic materials (mineral salt for example). Moreover, they produce many substances and heat. They too are eaten by consumers.

2. **Consumers.** An ecosystem most of the time is studied through its organic mass. In an ecosystem, most organisms try to develop and support its organic mass. That category of organism is consumers. They mostly produce organic mass by consuming other organic mass and release part of that mass in the ecosystem. They too participate to the layout of the environment .

3. **Detritivors or decomposers.** As an organism lives, it releases (dead) organic mass. That organic mass is reused by bacterias to produce raw materials needed by the producers. They thus maintain the ecosystem ressources.

Each part of that classification is a part of the functional aspect of the ecosystem and participate to the previous cycle of life. That classification constitutes the base of the representation of the biotope in our model.

We represent ecosystems with a multi-level model. Some level are fixed “a priori”. We shall describe them later. The determination of the level lays on the following concepts.

Ecosystems are systems as described in the general system theory meaning they are made of elements in interaction. In ecology, the basic elements are individuals. So on, we should introduce individuals in our model. Clearly, we should use an individual based model on that level. Moreover, ecosystems are thermodynamical systems. We should take into account flows between ecosystems on a different level than the individual's one (as they operate on a different scale). Finally, those flows are well modeled by laws.Finally, ecosystems are SOHOS. That induces we shall define non-directionnal relations between levels and furthermore, and add dynamic scaling for emerging entities.

While studying the informations available concerning several natural aquatic ecosystems (the Seine estuary, for example) we noticed that these ecosytems could be separated into differents compartments, each one being a particular ecosystem. Clearly, that description is space-oriented depending of the localization of the compartment and its inner space. A level corresponding to those compartment should be adopted.

Definition of the holarchic hybrid model

Following the previous concepts, we propose a model suiting ecosystems features and allowing reuse of already existing model different by nature (law or rule-based, different scales).

The model is individual-based in the way it represents the different entities of an ecosystem. As a consequence, each entity has states (e-states, i-states or p-states) and behaviors. The behaviors correspond to the model used to model the dynamic of the entity. It could be rule-based or law-based.

Our model presents three levels defined “a priori”.

- **Individual level.** That level is the lower one in the holarchy of our system. It embodies entities that could not be decomposed. We introduce individuals and super-individuals at that level. Moreover, the elements of that level are described following the consumer-producer-detritivor model. Thus, one should question what are the links between a particular entity and the ecosystem. That level is clearly individual-based so behaviors of the entities are rule-based and entities have i-states.

- **Compartment level.** The space is a critical data in ecosystem modeling. We introduce the space at that level . Thus, a compartment is a single entity in interaction with other compartment (exchanging flows) and containing individuals. As ecosystems are SOHOS, individuals and compartments influence each other. The compartments have law-based behaviors and e-states. The e-states of the compartment correspond to global values considered homogeneous in all the space of the compartment.

- **System level.** Systems are non-spacialized entity corresponding to a set of entity. The link between those entities could be defined “a priori” or during the simulation. The first example of a system is the ecosystem itself. It is made of compartments and defines their relations. Moreover, phenomena occur at the scale of the ecosystem itself influencing all the compartments. The systems have e-states and law-based behaviors. During the simulation, different kind of systems could emerge, each one corresponding to a new scale. Moreover, phenomena with particular scales should be modeled through systems. It is important to understand that the phenomena occuring on the ecosystems level directly modify the compartment and thus influence too the individuals of the compartment themselves. Simultaneously, individuals modify their compartment and thus influence the ecosystem.

What will be modeled

We tested our model on a classic example of aquatic ecosystem. We will now describe it.

Our example is an ecosystem in which we study the influence of light and oxygen on a simple food chain. The light differs in many place of the ecosystem. The oxygen influences the behavior of the biotope.

The food chain is made of four species. The first population is made of planktons consuming mineral salt and producing oxygen depending on the light. Bacterias constitute the second one. They decompose organic mass and release mineral salt. The two last populations are fishes. The first of them feeds on planktons. The second have plankton and the first population of fish as preys. Both of them consume oxygen.

4 An ontology to describe ecosystems

As we propose a model, we also provide a tool to ease the modeling of ecosystems using our work. That tool comes as an ontology of our model.

What is an ontology

First, let’s remind what’s interesting in making an ontology. ’Ontology’ stands for a formal definition of the terms and concepts of a domain. While making an ontology, we start by enumerating the crucial concepts of the domain. Then, we should give a clear definition of each one.

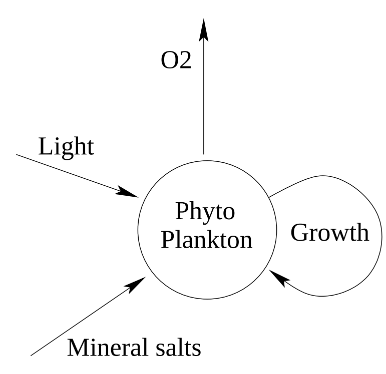

Figure 5: Producer - phytoplancton

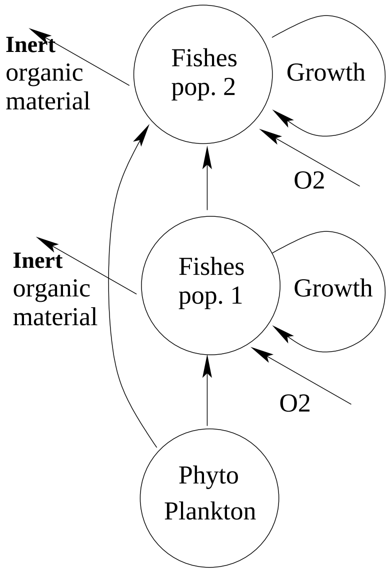

Figure 6: Consumer - food chain

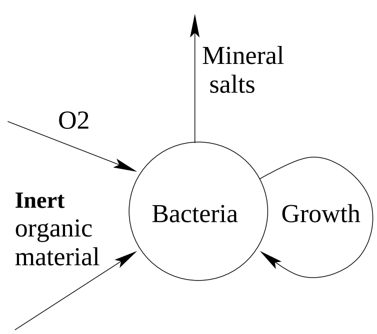

Figure 7: Decomposer - bacteria

Finally, we should obtain a collection of concepts. Therefore, links and relations between those concepts have to be established. We can distinguish different types of links. A concept could be a precision of another one. In that case, it is said that one of them ”inherits” from the other. Concepts could have relation when a concept “has something to do” with another. That formal link determines what other concepts should be considered when you think about one of the concepts.

Finally, ontology precises the view of a domain, gives an explicit definition for each concept and highlights the assumption of our view. We use Protege2000 (pro, 2000) to design our ontology. Understanding and following the assumption of our model is natural while using that ontology to study a particular case of ecosystem.

Our ontology applied to the example

The following demonstration correspond to a down-top approach, but we can also use a top-down one to model our ecosystem. First, the example shows us a food chain composed of four species. As we want to introduce the species, we should first determine if they are consumers, detritivors or producers.

- **Plankton.** Plankton produces oxygen, consume mineral salt and multiply without consuming organic mass. it clearly corresponds to producers.
- **Bacterias.** Bacterias use the organic mass to produce salt through decomposition. They are detritivors.
- **Fishes.** As far as we know, fishes are consumers as they consume organic mass to produce their own.

As we define those species, we see that producers, consumers and detritivors must be linked to a particular individual-based model (individual or super-individual). We should now think about the way we will represent them in our system. As we made that choice (individual for the plankton and fishes, super-individual for the bacterias), we must define the behaviors of our individual. Each category has already defined behaviors that can be reused. We can also introduce a new rule-based model that will be used by the behaviors to simulate the photosynthesis for example. Simultaneously, the ontology asks us which way the individuals will be localized in the space. Therefore, we should look for a localization suiting our needs. It will also define the way the space will be modeled. We choose a 2D coordinate localization. The ontology induces that we should choose a space corresponding to that kind of localization. We then choose a 2D continuous space.

The lowest level of our simulation has been achieved. Fortunately, new questions has been revealed by our ontology. Mineral salt, oxygen, light and organic mass needed by the low-level entities have to be modeled. First, should

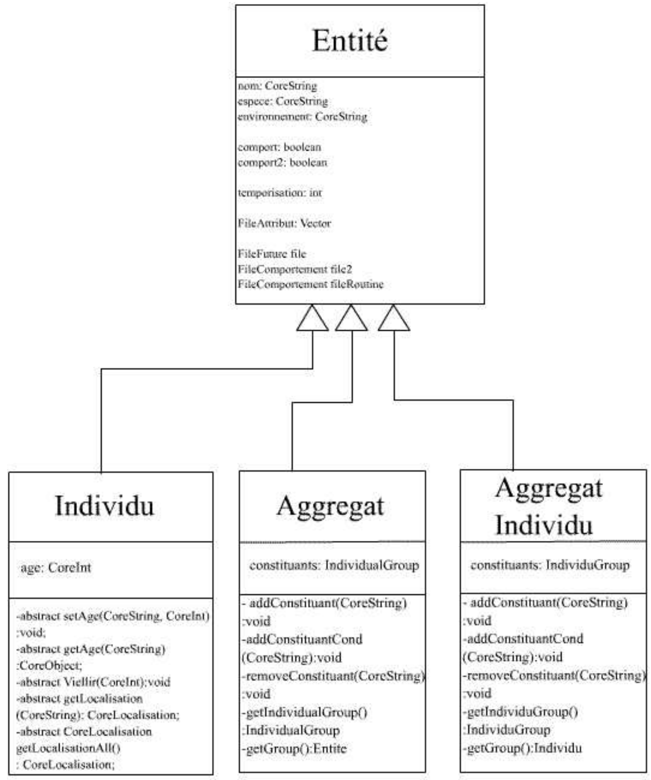

Figure 8: An exemple of Class:the class Entity and its child

we introduce them as producers, consumers or detritivors ? The best way to reintroduce them is placing them at the compartment level as they correspond to e-states. The light is a criterion to distinguish the different compartment. The mineral salt, oxygen and organic mass quantities vary in a compartment depending of its settlement. Therefore we define three e-states. Their behaviors are simple. Oxygen, mineral salt and organic mass don't vary by themselves nor have subtle interactions with other elements of the simulation so they have no behavior. Light could vary depending on the time so we can add a behavior making it lower and higher (actually, we won't).

During the previous step, the ontology led us through the definition of our compartments. They will have four e-states (O^2, mineral salt, light and organic mass). The ontology asks us the types of space model used with that compartment. We have already chosen a 2D continuous space one. It only remains to define the behaviors of our compartment. A compartment exchanges fluxes with its neighbors. So we should define a law-based model corresponding to the fluxes between the different compartments. When defining it, we now realize that we must precise how compartments are linked. Therefore, compartment have a neighborhood and values determining how much they are connected to each neighbor. A compartment has also a localization corresponding to the space model "neighborhood".

The informations concerning the neighborhood appear at the level of the ecosystem itself. That one constitutes the higher level of our simulation and embodies the compartments. It also defines the neighborhood as its own space. Its behaviors correspond to the global exchange of the ecosystem with the "outer world" (classical notion in ecology).

To conclude with, the ontology naturally guides us through the modeling of a simple example of ecosystem respecting the concepts and assumptions of our own model. That step ends with the choice of classical law-based or rule-based models to simulate the behaviors of each entity. That modeling step achieved, we can now go to the simulation step.

5 From model to simulation: a distributed implementation

The previous work provides us with a model corresponding to our ecosystem and the aspects we want to study, but the purpose of this model is to give birth to a simulation, allowing us to increase our understanding of the ecosystem. Therefore, we are conceiving a platform corresponding to our model and directly linked with our ontology.

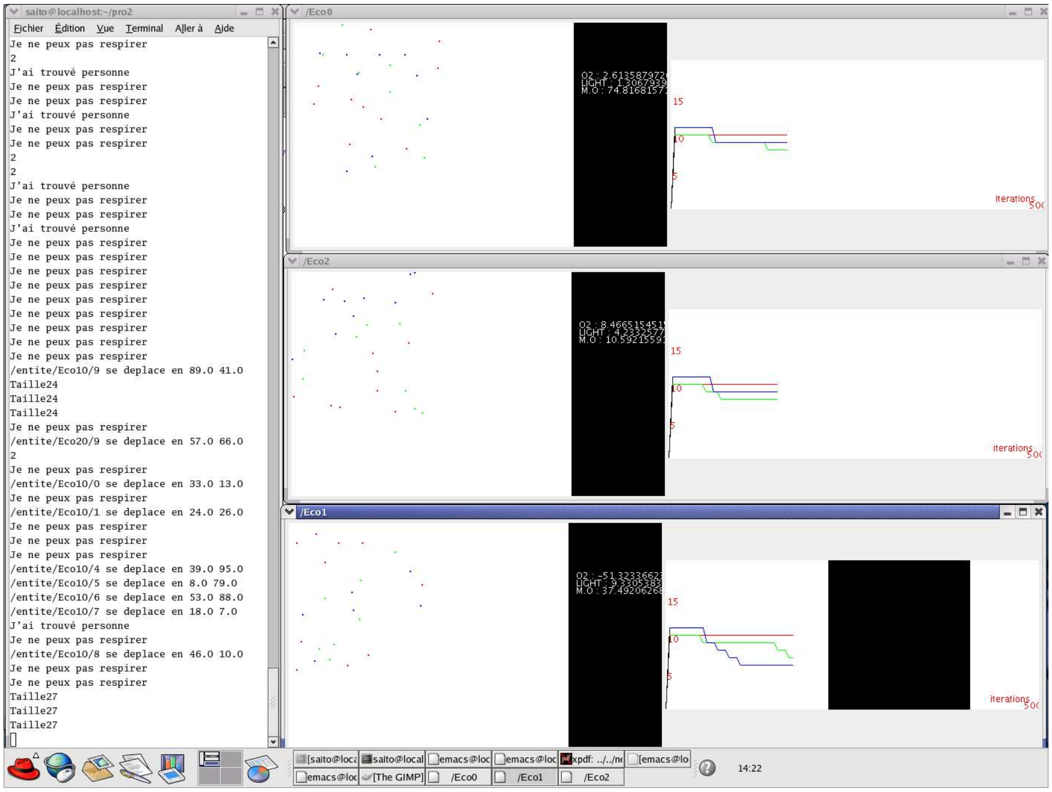

Figure 9: Screenshot of a simulation

Simulation framework description

First, let's sketch that the framework will follow the concepts of our ontology. We will based the framework on active objects as they suit well the individual-based model chosen in our hybrid model. To easily conceive a simulation tool using active objects, we program in java using ProActive. ProActive (Baude et al., 2000) is an API enabling the conception of distributed active object's applications. Therefore, we implement all the concepts of our model in a reusable way.

Our framework lays on many classes:

- **Entity.** Every object acting during our simulation is an entity (i.e an active object). It has states, behaviors and a fixed cycle of life.

- **Aggregat (i.e systems).** Aggregats are entity containing other entities.

- **Compartment.** Compartments are aggregats defining a space and making part of a neighborhood.

- **Individuals.** Individuals are indecomposable entities localized in a compartment. We distinguish three types of individuals: single individual, super individuals and possibly e-state with behaviors.

- **Behavior.** A behavior is a task done by an entity during its life-cycle. Behaviors correspond to the computing application of a model onto an entity. Behaviors can be executed one time, or in a cyclic way.

- **Space.** A class representing the main characteristic of spacial representation in our simulation.

- **Localization.** A class representing the main characteristics of localization of an entity in a space.

- **Living Part.** Those classes represents the main informations needed to incorporate a consumer, a detritivor or a producer in a simulation (inducing the model that correspond to the photosynthesis, decomposition ...).

Many other classes have been developed in addition to those ones that are purely computational, with no meaning in the ontology. Our goal is to provide an easy to reuse and complete framework. Moreover, the final platform will be completed with an interface guiding ecologists through the conception of a simulation without coding.

Framework test on our simulation

The test of our framework on the simple example previously developed highlights some aspects of our work. First, developing a simulation respecting the model tends to be easy as little programming needs to be added. Hopefully, the classes and functions already developed fulfill all the operative aspect of the simulation.

Despite that fact, there is a blatant need to incorporate existing models to make a behavior library useful for ecologists.

The simulation corresponding to our example shows interesting results. In some case and depending on the neighborhood constitution and on the light ratio, compartments tend to eliminate some species. Thus, some compartments specialize in producing oxygen and are full of plankton and bacterias. In that case, the first population of fish only feed on the other fish and live in a compartment deprived of planktons. In other case, the three compartments tend to a moderate equilibrium. In that case, the species appear in every compartment corresponding to a certain ratio of individuals for each one of the species.

6 Conclusion

Some aspects of complex organizations in aquatic ecosystem, can be modelised according to the approach previously presented.

The next step of our work is thus to confront in-situ experimental behaviours with some computer based behaviours obtained with the proposed simulation. Using more complex descriptions for the biodiversity, we will be able to produce some explicative and predictive modelizations for auto-organization phenomena in biological systems.

To realise these perspectives, we have already obtained many scientific informations on the Seine estuary which is a very complex ecosystem in the north of France. Last years, many studies have been made to give precious informations for understanding the complexity of this natural environment (Guézennec et al., 1999). Next years of our studies will concern the development of concerted models taking into account information from specialists of the Seine estuary ecologist .

GRANTS

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