Designing an Information System for the Preservation of Insular Tropical Environment in Reunion Island
Integration of Databases, Knowledge Bases and MultiAgent Systems by using Web Services

Noël Conruyt, Didier Sébastien, Rémy Courdier, Daniel David, Nicolas Sébastien and Tiana Ralambondrainy

Abstract. Decision-makers who wish to manage Insular Tropical Environments more efficiently need to narrow the gap between the production of scientific knowledge in universities, or other labs, and its pragmatic use by the general public and administrations. Today, one of the main challenges concerning the environment is the preservation of the biodiversity of ecosystems that suffer from urban and agricultural pressure. As we can only protect what we know, it is all the more important to share expert knowledge about habitats and species by using Internet in order to educate the public about their wealth and beauty. Based on Reunion Island, and taking into consideration an expected population growth of over 30% in the next twenty years, we are working to predict the human impact on this closed territory. To help tackle these two questions about biodiversity and land consumption, we have designed an Information System (IS) in the framework of the ETIC program. Our aim is to enhance insular tropical environment research in order to help the Reunion National Park to manage its protected territory. On the one hand, biodiversity research is handled statically, using knowledge bases and databases, to enhance Systematics and ecological university research. On the other hand, spatial planning concerns are treated dynamically, using multiagent systems to simulate population densification movements. These software technologies have been implemented and integrated through a common architectural system in the ETIC program. They were conceived using Web Services that allow each module to communicate its functionalities and information with one another, as well as with external systems.

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1. Introduction

Insular ecosystems are particularly rich, with remarkable endemism rates, but they are also extremely fragile and often highly deteriorated. In order to better protect biodiversity and natural spaces, expertise on these ecosystems needs to be propagated using information and communication technologies so that the most recent updated information may reach every-day people and activists. The more people know and understand their natural environments the more they will respect them and become emotionally attached to them. Policy makers, experts and members of civil society representing European, national, regional and local levels are aware of the necessity to preserve the patrimony of tropical islands\(^1\). The natural heritage of Reunion Island is rated as one of the official “hot spots” (figure 1) in terms of world biodiversity [23].

Figure 1: The World is an Island: Reunion, a “hot spot” with its Natural Property.

The biological diversity of the islands in the South West Indian Ocean (Madagascar, Comoros, Mauritius, Reunion, the Scattered Islands) is still rich despite important anthropic pressure, which is increasing from year to year. The Reunion National Park was created in March 2007 in order to fix the limits of Natural Property (42% of the island’s surface). Henceforth, authorities are preparing to apply for World Heritage Status in 2009 [31]. The Green Energy Revolution, a vision of Reunion Island in 2030,\(^2\) is another governmental project that is to deal with energy production and storage, high quality environmental habitats, and intelligent transportation and ecological tourism. The problem is that communication on these projects has thus far been unidirectional. The general public needs to be more involved in planning in order to optimize the population’s participation towards the sustainable development of their island. There is a real need for investment in mid and long-term communication services. It is not sufficient to merely

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\(^2\)http://www.gerri.fr/, visited on 09/29/2008
focus on saving energy and managing resources. For the future of ecology, the exchange of information is the key towards awareness of our shared natural heritage. The challenge for Reunion Island’s inhabitants is thus to manage territory that is closed, just as the world itself (figure 1).

There is a need for collective tools if we wish to manage common property [40]. The quality of information and the way it is delivered is of utmost importance in the shaping of public opinion. The university’s role is thus to deliver qualitative data and expertise in order to help decision-makers make the right conservation choices, as well as to help inform and educate the general public. The University of Reunion has accumulated a large amount of qualitative observations, data, information and knowledge on ecosystems over the past forty years. This information may be found in laboratory checklists, collections, museums, literature, charts, maps, images, video files, audio files, and individual databases, yet is hardly exploited by anyone except the authors themselves. Moreover, in environmental studies, progress in research often depends on the information produced by social sciences, such as sociology, economics, and law. Yet, for various reasons (methodological, communication problems, intellectual property rights, etc.) the exchange of information between these different fields of study is still facing difficulties. New solutions are needed to treat global and complex problems in the information age.

The ETIC program was created in order to find solutions for research and knowledge enhancement of natural Insular Tropical Environments using Information and Communication Technologies3. It is based on collaborative methodology, stressing partnerships with researchers and associations who wish to share their skills in Systemics, Geomatics, Biomatics, or other domains of knowledge engineering and collective intelligence, by using telecommunication and computer science, with content producers, editorial boards, scientists, educators, decision-makers, enterprises and end-users.

This chapter will briefly present the insular tropical environment context of Reunion Island. We will explain the enhancement methodology we have set up, and the architecture used to design our IS for environmental preservation. We will illustrate this with an example and describe some software components and services that are part of our artificial intelligence research for the management of biodiversity and environmental sciences. All these components are presented from a methodological viewpoint in order to address questions concerning insular tropical environments. Finally, we will introduce the Web Services that we have developed to link applications and services, and discuss the next step for the IS in the fight to protect our natural heritage, by illustrating its usefulness for decision-makers in regards to the Reunion National Park4.

2. The preservation of Reunion’s insular tropical environment

Reunion is a 2,500 sq km island located in the South West Indian Ocean (figure 1). In the coming years, this French overseas department will have to deal with numerous growth phenomena and with their related consequences. With regards to land development, Reunion is facing the challenge of accommodating an ever-greater population while, at the same time, preserving its agricultural soil and its exceptional landscapes and local species.

By 2030, the island population will increase from 775,000 to 1,000,000\(^5\), which represents an impressive increase of over 30% in 20 years! This demographic trend leads to a number of problems, especially concerning housing. Taking into account the 225,000 additional people, the need for housing creation is estimated at 150,000. Thus, even if one puts forward a hypothesis of high density, the future of the island will result in an inevitable increase of the demand for urban land.

The rush towards urbanization is leading to greater anthropic pressure, which is increasing from year to year, on natural and agricultural spaces. This is an important problem for land and ecosystems management of the territory. Indeed, 50,000 hectares are occupied by agriculture that, with its 15,000 related jobs, has a powerful influence on the island’s economy. Protecting the agricultural sector, including sugar cane plantations (the most important exploited resource), is therefore an additional priority; it is necessary to limit their consumption by urbanization and to prevent urban sprawl on the best farmland. Likewise, there are more than 100,000 hectares of natural areas, harboring fragile species and rich biodiversity that need to be protected and controlled.

Henceforth, one of the main priorities for Reunion’s government administrations (Regional and Department Councils, the Prefecture, the Reunion National Park) is to improve ecosystem management that is conditioned by ZNIEFF\(^6\) inventories. The island’s heritage, whether it be the land ecosystem (such as tropical forests) or the marine ecosystem (such as coral reefs) is altogether subject to growing economic pressure (urbanization and structural spatial projects, agricultural and industrial development) and to large-scale impact from tourism and leisure activities. The function of these natural areas is of the highest importance for the ecological equilibrium of the island as a whole.

Considering the situation from the perspective of sustainable development, urbanization policy concerning land management on Reunion Island needs to be as clear as possible. Many administrative documents treat urbanization at different levels on the island. Each one has its own importance because ecosystems management has to be considered both on the macro and micro levels. The SAR, Regional Land Development Plan, and SCOTs, Territorial Coherence Schemes, define large areas that have to be protected from urbanization according to global needs of biodiversity, while the PLUs, Local Urbanization Plans, deal with the localization

\(^5\)http://www.insee.fr/fr/regions/reunion/, visited on 09/29/2008  
of very specific areas, and species, to be protected from anthropic pressures in cities and districts.

In this context, territorial futurology, creating models and tools that will give us indications about the island and its evolution, is of capital importance. These models, which are part of the ETIC program, offer the possibility of testing the coherence of different management scenarios, and are intended for the use of policy-makers as tools to assist them during the decision-making process regarding choices that will affect our tomorrow, such as the elaboration of the SAR, SCOTs and PLUs, and their effective execution over the years.

3. Designing an Information System for environmental protection

ETIC is a publicly funded data and knowledge enhancement program, based on Reunion Island, whose goal is to develop innovative ideas and ICT solutions for the management of biodiversity, ecology and ecosystems research contents. As part of the natural environment, biodiversity has been defined as “the variety of life in all its forms, levels and interactions. It includes ecosystem, species and genetic diversity” [19]. The program was created in 2004 at the University of Reunion for research enhancement of Insular Tropical Environments, by using Artificial Intelligence techniques such as Knowledge Engineering for building expert systems, Collective Intelligence for building multiagent systems, and Information and Communication tools such as content management systems for sharing information. Indeed, the first step to protect our insular tropical environment is to better educate citizens about its richness because we can only protect what we know!

ETIC is based on several thematic projects and a collaborative methodology, stressing partnerships between researchers, educators, decision-makers, enterprises, associations and end-users who wish to share and communicate their environmental data and knowledge off and online. With the help of computer scientists, web designers, programmers and graphics experts, the common goal is to participate in the construction of an Information System (IS) for environmental management on the Internet. Contents include terrestrial and marine biodiversity descriptions about specimens, species geography, ecology, photography, taxonomy, and bibliography contextual information on Reunion Island.

3.1. Enhancement methodology

Our approach is intended to be interdisciplinary, entrepreneurial and constructivist [1]. It combines experimentation and theory in a network of exchanges so as to satisfy and anticipate the use of scientific contents by a variety of socio-economic players.

The ETIC program is structured according to enhancement projects, founded on the meeting of professionals (producers and editors), and the anticipation of needs of end-users in tropical insular environments. This participatory approach on the part of researchers is strongly motivated by the possibility of adding value
and distributing their research results through product-services on the Web\textsuperscript{7}. With the support of project leaders, the generalization of this approach to other content areas within the program has considerable potential.

Knowledge enhancement and diffusion has two forms within the IS:

- A collaborative local network site for researchers that brings together tools (software and services), functioning within a secured infrastructure (Intranet), in order to model interoperable data and knowledge. This \textit{upstream enhancement} or e-research activity is an iterative and creative process for the development of application generators.
- An Internet portal accessed by the general public, which is divided into two parts “sea and land” with the development of applications in thematic projects, \textit{i.e.} instances of the tools mentioned above. This \textit{downstream enhancement} site offers information relative to environmental questions and presents e-learning activities.

\textbf{Upstream enhancement}

The Intranet portal allows for the enhancement of scientific information (knowledge and data) within a common architecture while assuring their interoperability through Web services. For biodiversity monitoring, Systematicians and biologists use IKBS (Iterative Knowledge Base System) as static personal knowledge management software on the micro level of specimens and taxa\textsuperscript{8}. For spatial analysis and visualization, ecologists and geographers use ArcGIS (ESRI Geographic Information System) for data storage and management software on the meso level of populations and biotopes. For regional planning, specialists in Systemics and Geomatics use GEAMAS-NG (Generic Architecture for Multiagent Simulations - New Generation) as dynamic collective knowledge management software at the macro level of habitats and ecosystems. An information management scenario on natural forest biodiversity preservation will be explained in section 3.3.

For interoperability of marine and terrestrial information, the other objective of upstream enhancement is to represent metadata of applications in a structured and standardized way. The functionalities of different applications can be generalized in software and services by an inductive process that enriches them as common tools dedicated to more general tasks. The personal, ecological, photographic, geographic and terminological data and documents of biology experts are stored thanks to five dedicated database modules: a Directory to authenticate users, a Biodiversity module to monitor specimens and taxa, a Multimedia module to share documents, a Cartographic service to geo-reference data and a Thesaurus to define specialized terms and illustrate them.

\textsuperscript{7}Product-services are also called e-services in the digital age: they are internet based electronic services

\textsuperscript{8}Taxa are the names of ranks in the scientific classification: Species, Genus, Family, Order, Class, ...
Downstream enhancement

The Internet portal presents thematic projects proposed and led by independent volunteers: Herbarium, Natural Risks, Littoral Information System (SIL), Medicinal and Aromatic Plants (MAP), Tropical Environment Management (GET), collective management of animal waste (BIOMAS), Coral Reef Monitoring (COREMO), Hydrogeology of the “Piton de La Fournaise”, etc. These applications may be developed in collaboration with non-university partners such as the ARVAM\(^9\) organization, or the VO\(^10\) association.

For example, “Life in the coral reef” is a structuring project which proposes to unite the skills of content producers (University of Reunion laboratory researchers, educators from independent groups for nature conservation), content editors (IREMIA, Multimedia Centre) as well as professionals and students working within master’s degree programs in Computer Science, Indian Ocean Communication, Tropical Environment Management Sciences, or Computer Graphics schools (ILOI\(^11\)). The potential for information and communication calls for an analysis of the usages\(^12\) of projected services on a co-design platform, uniting all at once the ETIC community of project leaders, researchers and users.

This constructivist approach gives new ideas for software development to computer scientists in return. For example, in order to manage coastal zones, we can offer access to a complete series of data concerning biodiversity, beach erosion, coral bleaching, protected areas, and drainage basins in a Littoral Information System (SIL). This general application is connected to ArcGIS that may be consulted or modified in the Intranet by biogeographers. As we also develop and enrich knowledge of experts in Systematics with knowledge bases such as “Corals of the Mascarene archipelago”, which is done by using IKBS, the identification tool should communicate with SIL by offering access to species information on a map of reef biotopes. In the end, we are able to create behavior simulations with multiagent systems, for example on the interaction between corals and fish, or a chemical pollution intrusion in the lagoon, etc. The finality is that these tools become instruments in end-users’ hands, \(i.e\). really used in every day contexts [10].

\(^9\)http://www.arvam.com/, visited on 09/29/2008
\(^12\)In the context of a user-centered design research at the University of Reunion, a creative or co-design platform is a physical or virtual meeting and communication space for product-services to be developed with user input concerning expected needs being a key factor in the creative process. These e-services are developed in projects by a team of content producers (researchers), packaging editors (designers and programmers) and distributors of the final product (operators). The multimedia platform is similar to those which are met in the film and broadcasting industry (TV-Net style). Products and services are developed from a well-focused response to clear questions with specific tasks to be solved, with the help of end-users so that the new products most directly match the expected uses of the projected services [37].
3.2. Architecture of ETIC Information System

All of these marine and terrestrial thematic applications are at different levels of development: mock-up, prototype, product-service. They can make use of transverse services such as the Directory for authenticating users. Some of them are founded on a database management system developed in PHP-MySQL but are not yet interoperable. They can also rely on software for knowledge base management (descriptive modeling with IKBS), geographic information gathering (spatial analysis with ArcGIS) or multiagent system behavior simulation (GEAMAS-NG).

The whole constitutes the IS for Tropical Insular Environment Management Support, of which the proposed functional architecture may be found in figure 2. It is modeled as a SOA (Services Oriented Architecture) middleware with a hub of Web Software Services (WSS) and Web Component Services (WCS) on demand. This hub of Web Services is detailed further in section 6.

3.3. Example

The ETIC program is structured according to projects for which the long-term objective is to make them interoperable in relation to environmental questions. For example, concerning the protected areas of the Reunion National Park, it is imperative to define the specific elements of biodiversity in the primary forest.

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A product-service is an application or software tool that is really used in the domain area, whereas a prototype is something usable or occasionally used.
zones, the types of anthropic pressure on them (pests, urban scattering) and the expected evolution in 10 year’s time. The first step is to be able to identify the plant specimens, at least their Genus names. The scenario in figure 3 shows the tools that we are developing to help find answers to these questions.

Biodiversity information comes from expertise in Systematics and Ecology. In order to manage specimen and taxa information, we rely on knowledge bases and databases. These technologies are used in order to get all the descriptive and static details of biodiversity information. Different modules for collecting ecological, geographic, taxonomic, photographic and terminological data have been designed to constitute authored information sources. But to access this general information, one important entry is to know the name of the specimen under study. For this task, an iterative knowledge based system called IKBS has been built to help specialists in Systematics define descriptive models of a domain. For example, this could be a genus of orchids for which one may describe cases, and let people identify the name of a specimen through questions. These two steps form the static kernel of data and knowledge acquisition of our ETIC IS. It is complemented by a temporal follow-up of orchid species and spatial analyses of the protected areas through a private Geographical Information System, ArcGIS\textsuperscript{14}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{The information management service on natural forest biodiversity}
\end{figure}

When the wealth of a natural zone is known, decision-makers need other tools in order to manage these ecosystems - to analyze the human consumptions of the territory that comes from the urban and agricultural pressure on these habitats. The objective of SAR, SCOTs and PLUs is to explore scenarios for the evolution of the growing population. In our IS, these simulations are dealt

\textsuperscript{14}http://www.esri.com/software/arcgis/, visited on 09/29/2008
with using a multiagent system called GEAMAS-NG that tests behavioral models of agglomerations, i.e. urban extensions. This simulation process constitutes the dynamics aspect of our method.

The next part of this chapter will present both static and dynamics aspects of environmental information management. After a brief overview of biodiversity descriptive knowledge and data management software and services, we will focus more precisely on modeling dynamics using multiagent technologies.

4. Modeling biodiversity static information with knowledge bases and databases

Systematics is the scientific discipline that deals with listing, describing, naming, classifying and identifying living organisms [22, 42]. In our research, we focus on populations of specimens between the taxa and organ levels of biodiversity research [20].

The originality of our insular tropical biodiversity management method is that we concentrate on natural objects that are specimens in the field (living specimens), as well as specimens in museums (collection specimens). Experts in biology at universities have studied them intimately for years and are the only persons able to correctly identify species, which is an important step in the process towards offering access to more specialized information to non-experts. Researchers build their personal or tacit knowledge [29] by observing species in the field and in their laboratories under the microscope, then interpreting them with descriptions. These described objects form the basis for the development of their formal or explicit knowledge in monographs that constitutes their authority in their area of speciality.

The core of the ETIC IS platform is the integration of knowledge bases and databases about biodiversity knowledge and data by using Web Services.
4.1. Knowledge bases

In this part, we will briefly summarize the main functionalities of our knowledge engineering method. The complete methodology of knowledge management can be found in [9]. Knowledge base applications are instances of a Knowledge Based Management Tool called IKBS. This Iterative Knowledge Base System lets specialists define an Object-Attribute-Value morphological descriptive model of the domain knowledge (input), and describe cases (output) based on this ontology (figure 5). The knowledge acquisition phase can be repetitive because IKBS applies the scientific method of Popper [30] in biology (conjecture and test) with an iterative process of knowledge management (figure 6):

1. observe and familiarize oneself;
2. represent observations, i.e. make a descriptive model and related cases;
3. build hypotheses from pre-classified descriptions, i.e. generate identification keys (supervised classification);
4. test and use them with new observations, i.e. identify new specimens;
5. refine the initial knowledge (new characters, cases and classifications).

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**Figure 5: Biodiversity knowledge bases management system within the IS**

**Figure 6: IKBS methodology of Systematics knowledge management**
After an automatic classification process based on tree induction of pre-classified cases, end users are able to identify new descriptions with a questionnaire. End-users proceed by photo-interpretation of specimens to obtain a genus name, or by observing microscopic specimen elements under a binocular microscope to identify a species name [7].

4.2. Databases

The main database is a biodiversity module, i.e. a database of objects that stores, organizes and presents scientific data about field observations, collected specimens (samples) and taxa descriptions. Other database modules (i.e. directory, multimedia, thesaurus and cartography) complement this central module:

1. the directory gives access to the subjects, i.e. the individual and community researchers with their profiles in a card index;
2. the multimedia database manages all types of documents (photo, video, sound, etc.) that can be indexed to specimen objects;
3. the thesaurus will be an illustrated glossary that stores the meaning of Insular Tropical Environment vocabulary;
4. the cartography is a tool for georeferencing data on a map (made with the GoogleMaps API).

All of these modules are linked by Web Services so as to constitute a modular, interoperable and integrated biodiversity specimen and species database management system (figure 7).

The data entry process in the biodiversity module is organized around the memorization of specimen information, which is collected in notebooks by biologists when they inventory biodiversity. It has been structured in five edition tasks (actions) that follow the daily work of monitoring specimens in the field:

1. Origin of specimen, where was it found?
2. Short description, what was observed?
3. Taxon identification, what is it?
4. Status of specimen, i.e. sex, nature, state, fertility, development stage.
5. Label of specimen if it is to be put in collection.

In addition to this internal specimen information in the biodiversity module, the surrounding modules manage external contextual data such as the location of the specimen (space identification with the Geolocation system), the identity
of the subject (who is the observer in the Directory), the image or video of the specimen with associated metadata in the Multimedia Database (figure 8).

Figure 8: ETIC process of biodiversity data management

5. Modeling ecosystem dynamics with agent technology

This section introduces first the interest of using multiagent systems for ecosystem dynamics representation, then the behavioral model proposed and implanted in the GEAMAS-NG simulation toolkit is detailed. Finally, several examples of multiagent systems participating in the ETIC IS are presented.

5.1. Agent technology and complex systems

Understanding and Analyzing complex systems

Complex natural and social systems are the subject of many studies aimed at understanding their characteristic dynamics and functioning. The frightening complexity of these systems constitutes a challenge for computer science modeling [35]. The complexity of a system involves an important number of components, which are joined in such a way that it is difficult to separate them. This duality determines two dimensions of the complexity [3]:
• First, the distinction of several components imposes the obligation to find a way to reduce, to organize the system complexity, and to describe suitable components.

• Second, the connection between these components involves dynamic aspects of the system: they are linked with interactions that are dynamic relationships by means of a set of reciprocal actions among components. Interactions consist in exchanges of actions, from which the result of the system will emerge.

Therefore, a complex system is internally driven by interactions between its components whose result exceeds the contributions of individual components. In complex systems, individual components make decisions in accordance with various rules, on the basis of local, rather than global, information. Computational tools should provide intelligent capabilities to simultaneously integrate, in the same frame, a variety of information, and to perform a synthesis of events, which may follow. The boom of computer science in systems modeling during the past twenty years has greatly increased the understanding of complex systems by using virtual simulation [5].

The most notable difficulty of multiagent systems is to organize the dynamics of the ecosystem in question as a society of interconnected autonomous agents, that matches the complexity of the real world, and then to evaluate the results of the simulation. Figure 9 synthesizes some of the key activities by defining an iterative incremental cycle used to control the whole process of behavioral model development built with the help of relevant experts.

This cycle describes four major activities:

1. Agent identification and definition of their attributes.
2. Defining behaviors that organize all the actions and influences the agents can undertake (with a methodic attention upon contextuality of the interacting elements).
3. Associating spatio-temporal environment to the agents.
4. Processing simulation scenarios on specific existing ecosystems on Reunion Island.

After each cycle, the simulation results are analyzed by relevant experts who validate the model. This leads to a new cycle, which aims at refining existing dynamics or at inserting a new dynamic in the model.
Emergence of phenomena

We have seen that what makes a complex system is the presence of interactions among the individual components of the system. But another property is the effect these relationships have on the behavior of both components and system. In complex systems, these relationships are at the root of emergent phenomena and constitute the key feature in almost all cases.

Emergence refers to the way the interactions among system components generate unexpected global system properties or behavior not present in any individual component taken separately. The treatment is centered upon the bottom-up approach, which offers a path of discovery towards possible solutions. While individual components of the real world are relatively simple in their behavior, when interacting, the collection of components turns out to be a richer structure, having a level of complexity greater than any one of its parts.

A good example of emergence is the organizational structure of an ant colony [16], achieving things that no individual ant could accomplish. All activities are carried out by individual ants acting in accordance with simple local rules and information. There is no master ant overseeing the entire colony and broadcasting instructions to individual ants. Interactions among ants give rise to patterns of global work allocation, which could not be predicted nor arise in any single ant.

Another example is that of shoals of fish that appear in lagoon simulations under particular conditions. These emerging shoals, which have their own behavior - collective behavior - exist in the simulation system instead of the hundred or thousand individual fish belonging to them. This provides significant interest for system comprehension, and offers the advantage of a drop in complexity during simulation.

One of the important characteristics leading to this kind of organization is that of the conditions under which a phenomenon emerges. In geophysical complex systems, this point of view has led to the concept of Self-Organized Criticality [2], to explain the “repeatability” of phenomena in nature. Such systems are driven by highly non-linear behavior; a small external perturbation could generate a large-scale phenomenon at a critical state of the system, but without predicting when it may appear. The system is therefore managed by a property that is unpredictable, but at the same time, the appearance of the phenomenon arises from instabilities, in which a small change in a component state can unbalance the whole system state, causing disasters. The critical state is thus seen as the trigger for emergent phenomena. This consideration gives importance to individual actions, which work toward the elaboration of the phenomenon, and therefore its organization.

One important result of this approach is to consider emergence (i.e. an emergent phenomenon) as a self-organized structure. This leads us to assimilate emergence in terms of self-organization. A computational model intended to develop simulation applications of complex systems should then propose an architecture in which emergent phenomena are dynamically created during simulation as they appear [18]. The result of the simulation is, on the one hand, interpreted in terms
of quantified results, and on the other hand, assimilated as self-organization of new patterns which model emergent phenomena.

Dynamically creating structures is interesting because it allows the system to keep track of phenomena, while they are being adapted throughout the simulation. For instance, in natural phenomena, the affected part of the system can, in its turn, influence the other components; it plays a role in the system for future behavior. An example is the case of a vegetal pest spreading through a primary forest. This emergent phenomenon radically modifies the forest as it will never again return to its primary state. Our assumption is thus based on the fact that once it appears, an emergent phenomenon becomes intrinsic to the system, and its new characteristics can no longer be inferred in the same way as before.

**Multiagent software engineering issues**

Software engineering issues require one to produce a complete toolkit, a virtual laboratory, that can design a large scope of dynamic systems, study the informational structure of complex systems and provide generic interfaces to set and control the simulation.

As the system complexity cannot be globally expressed, the challenge is to find a computational model able to:

- Represent and distribute complexity in individual elements.
- Represent the system dynamics as local interactions between agents.
- Provide editing tools to build simulation scenarios.
- Provide mechanisms so that simulation results emerge by interpreting local interactions.
- Provide optimized mechanisms to support large-scale simulation, which implies through interacting agents.

Propositions addressing these issues have been made through the GEAMAS simulation toolkit and its latest version, GEAMAS-New Generation. This version extends the capacity of the previous one to support a larger simulations scale (more than 100,000 agents). GEAMAS-NG features:

- Dynamic-Oriented Modeling [26], that models real systems by representing their intertwined dynamics through a set of monothematic dynamic sub-models.
- Temporality time management model [25] [38], that eases agent description and optimizes execution.
- Configuration tools [27], that provide scenario description languages and original map-based initialization.
- Emergence manipulation mechanisms [15], that enable reification of emergent phenomena that occur during ecosystems simulation.
- Parallel and distributed simulation execution [38], that supports large-scale simulation execution by dynamically distributing agents on the execution infrastructure.
• Advanced observation of simulation results [32], that provide pertinent visualization tools specific to agent concepts such as agent interactions and conversations analysis.

Considering that the aim of this section is to focus on modeling ecosystems dynamics, let us now elucidate the first item mentioned above - Dynamic-Oriented Modeling.

5.2. Dynamic-Oriented Modeling

Modeling dynamics in a multiagent system

Modeling a complex system into an agent-oriented simulation model is not an easy task as experts must define the agents that interact with each other in an environment. Indeed, agents usually participate in several dynamics thus intertwining them. This makes modeling more complex. In this section, a dynamic is defined as an association of a set of activities that participate in the specification of a major characteristic concerning the study of a phenomenon.

To model the system’s evolution, it is necessary to let some dynamics show through the behavior of the agents and the properties of the environment. Therefore, the greater the number of dynamics to consider, the more complex the design of an agent will be. We have described a modeling approach called dynamic-oriented modeling which puts dynamics at the center of the modeling process. This approach is a means to circumvent complexity.

The state of an agent is composed of all its attributes, and its behavior organizes all the actions it may undertake. These two sets can be divided according to the dynamic to which their elements are referred, and some modify/influence relationships can be established between the subsets obtained. Figure 10 illustrates a partition composed of 3 dynamics: A, B and C.

In the same way as the subset of attributes A shown in figure 10, some of the attributes, which are linked to a dynamic often have an impact on the behavior in connection with another dynamic. These particular attributes are the prevailing attributes of the dynamic to which they refer.

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15 environment as to be considered, in this section, on its multiagent definition, An environment provides the conditions under which an agent exists. Different environment types exist. Physical environments provide those principles and processes that govern and support a population of agent. Communication environments provide those principles, processes and structures that enable an infrastructure for agents to convey information [24]
Once this characterization obtained, the model can be divided into a number of sub-models equal to the number of dynamics to manage. Each sub-model is exclusively associated to one of the dynamics, and is called a Mono-Dynamic Model (MDM). The agent is instantiated in every MDM that models a dynamic in which the agent participates. Yet, in each MDM its state and its behavior are reduced exclusively to the subsets that deal with the dynamic of the MDM (figure 11).

**Coupling dynamics in a multiagent system**

Multiagent simulation, in the ETIC Information System, is used to address issues concerning the management of ecosystems that have spatial aspects. In this context of spatial MAS [33], agents are associated with a part of the space in the environment.

This characteristic enables one to use the environment as a coupling element between the different MDM. To do so, it is necessary to extract the prevailing attributes of the MDM from the agent’s subset of attributes, and affect them as properties of the surface associated with the agent. In this way, the information contained in prevailing attributes is available in the environment, and accessible by agents situated in other MDM (figure 12).

The modify / influence interactions between agents and prevailing attributes located in the environment are completely natural in the exchanges between agents and environment. Indeed, they result from the actions / perceptions that an agent can make in its environment [35].

A dynamic-oriented simulation thus leads to a layer-structured agent model. Each layer, called MDM, models one particular dynamic exclusively. Layers do not directly interact with each other, but use the environment as a place to share information. The results of the processing of a dynamic are written in the environment by the agents, located in the MDM representing the dynamic. These results are then perceived in the environment by agents of other MDM and can possibly be taken into consideration to determine actions they must undertake to process their own dynamic. In other words, this approach enables the organization
of information in independent modeling layers. As each layer is independent and represents a particular aspect of the real system, it is possible to configure a layer by interconnecting it with an information repository (see 5.3).

In this manner, the environment constitutes a flexible point where MDM can exchange information, while warranting independence between the MDM. In this context, the integration of one MDM does not affect other MDM.

A similar application can be conceived by replacing one of the MDM with a software layer, by associating the necessary calculations of the evolution of prevailing attributes with the dynamic that was previously managed by the removed MDM (figure 13). This software layer can be, for example, a cellular automata, a virtual map interfaced with a GIS, or a stochastic grid of values, for example.

5.3. Integrating heterogeneous information layers

This dynamic-oriented modeling is a key feature for the simulation of biodiversity on the scale of a territory. Every dynamic of the system can be represented as a Mono-Dynamic Model, for example, urban space, agricultural space, or natural space. Dynamics interact with each other through the environment. The multiagent simulation can then mix these dynamics to produce a global simulation. The results help policy-makers in their decisions concerning the ecosystem preservation. In collaboration with the CIRAD agricultural research center\textsuperscript{16}, we have developed two multiagent simulation applications based on this dynamic-oriented modeling.

The first one is the BIOMAS application \cite{12}, based on the GEAMAS simulation toolkit \cite{21}. BIOMAS simulates the effect of agricultural dynamics on ecosystems. It simulates collective organic matter fluxes transferred amongst a set of farms located within a territory. This model is initialized by data taken from a descriptive model with detailed information about crops, farms and agricultural stakeholders. Moreover, the spatial environment of the agricultural stakeholders is also coming from an external spatial model (figure 14).

The second one is the SMAT application \cite{14}, built according to the dynamic-oriented modeling introduced in GEAMAS-NG. It is composed of a set of monodynamic models, mainly urbanization models, natural models and agricultural models. In order to do this, the multiagent simulation model is initialized using static data about the ecosystem and the environment (see figure 18 in section 6.4). These data are contained in external databases and in geographical information systems.

With these two models, we have successfully run large-scale simulations on the scale of a territory for the dynamic evolution of a whole ecosystem, based on static data from the ETIC IS.

6. Binding static and dynamic knowledge through Web services layers

One of the major originalities of the ETIC IS is that the software, components and applications, previously introduced through web services in a coherent architecture, that covers all the modeling aspects of insular tropical environment, are interconnected.

6.1. Web services as support for integration and openness

In order to make our IS modular and interoperable, we have chosen to design it according to Services Oriented Architecture (SOA). As it is a web platform, we chose the Web Services approach [13], which provides a number of features and benefits.

Among the technologies used to implement Web Services, we chose the WS* technology whose specifications are based on SOAP and WSDL standards:
SOAP (Simple Object Access Protocol) is used to exchange messages. It is a RPC (Remote Procedure Call) protocol built on object-oriented XML.

WSDL (Web Service Description Language) is used to describe Web Services, their operations, messages used, the types of used data, and the used protocols. The WSDL describes a public interface that provides access to Web Services. This description is written in XML and indicates “how to use the service”.

6.2. Advantages of using Web Services in ETIC IS

Using Web Services structured the way we developed ETIC IS:

• Firstly, we have chosen this technology because it allows other IS to use our modules independently [28]. In this way, information stored in the ETIC IS is fully open and exploitable by other institutions [41].

• Secondly, it has modified the way we imagine connections in the IS itself. It has let us develop each module in a heterogeneous way, using the appropriate technology (PHP/JAVA/Flash Action Script). For example, the ETIC Directory is developed in PHP whereas the first version of our Multimedia Database [36] was relying on JAVA technology. Although we used different programming languages, these two modules were able to exchange secured information, thanks to Web Services.

• Thirdly, from a technical point of view, Web Services impose rigor that allows us to update our systems and services without losing the compatibility with older versions. Each new version of a service is indexed with a number, and the WSDL provides a way to implement the new client, but it does not impact on the older versions that remain fully functional.

• Fourthly, from a management point of view, using Web Services was a good choice. The ETIC development team has often changed. Because of this high degree of turnover, it was difficult to transmit the key points of our development from the previous engineer to his successor. Thanks to the Web Services (and particularly the WSDL declaration), it was not necessary for the new team to fully understand a service source code to use it as a client. It saved a lot of development time.

Using Web Services was of course important to facilitate communication with our IS, but it also helped us to improve its inner structure.
6.3. What are the ETIC services?

Because each module and software is dedicated to accomplish a precise task, each one provides some specific functionalities and dedicated Web Services. In this way, any thematic application or other IS can reach ours and decide to use one or the whole of ETIC services for its own purpose. But contrary to data consultation that is completely open, these clients need to be referenced in the ETIC directory if they want to add information in the ETIC IS. This security allows us to ensure the traceability of information injected in our system.

The implemented connections between ETIC modules are shown in figure 15. Of the five modules (Directory, Multimedia, Cartography, Biodiversity, Thesaurus) and three software (IKBS, ArcGIS, GEAMAS-NG) deployed now, all use Web Services as the client, and most of them provide services (figure 16).

<table>
<thead>
<tr>
<th>Web Services</th>
<th>Provider</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Directory Multimedia Biodiversity Cartography Thesaurus IKBS ArcGIS GEAMAS-NG</td>
</tr>
<tr>
<td>Directory</td>
<td>✓</td>
</tr>
<tr>
<td>Multimedia</td>
<td>✓</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>✓</td>
</tr>
<tr>
<td>Cartography</td>
<td>✓</td>
</tr>
<tr>
<td>Thesaurus</td>
<td>✓</td>
</tr>
<tr>
<td>IKBS</td>
<td>✓</td>
</tr>
<tr>
<td>ArcGIS</td>
<td>✓</td>
</tr>
<tr>
<td>GEAMAS-NG</td>
<td>✓</td>
</tr>
</tbody>
</table>

Figure 15: Connections between ETIC modules

Work is still in progress. For instance, the current version of the Cartographic Browser does not implement a connection to the ETIC directory. In fact, it cannot be used as a standalone module yet. Other modules that connect to the Cartographic Browser must process client identification independently. Moreover, none of the functionalities that are supported by the modules have a Web Service offering the possibility of distant interrogation of it yet (e.g., the remote use of the multi-criteria search of the MDB, see figure 16). Nevertheless, most of the principal services of this module have already been developed.

Independent of the fact that we have to develop new Web Services for each module, we also have to increase the integration of the existing services between modules. This integration must be the result of focus groups realized with biologists in order to provide them the necessary information when they need it. This fine-tuning is a Web Design concern because, for end-users, Web Services must be transparent.
6.4. Two layers of services adapted to two kinds of needs

The ETIC IS relies on two different layers of Web services (figure 17).

![Figure 17: Global transactions between IS components.](image)

The first one, Web Component Services (WCS), is dedicated to provide convenient remote access to the modules. These modules may be considered as autonomous Web applications for thematicians, but also as toolboxes for developers. By using this service layer, they can focus on the front-end graphical interface of their own application without losing time in developing low-level processes. The second Web services layer, Web Software Services (WSS), offers access to the Knowledge Engineering & Collective Intelligence (KECI) portal. This layer analyzes the nature of the request and redirects it to the appropriate application. It
fulfills advanced functionalities, like those described in the knowledge production layer. In this frame, the professional software suite “ArcGIS” introduces complex generic processes in order to add geospatial analysis to our platform.

If thematicians are able to feed and use modules on their own, they still need modeling experts’ help to assist them, in order to use the knowledge production software and stimulate the emergence of new knowledge from data. We thus notice the need to connect modules (static knowledge) to the software (dynamic knowledge). From a technical viewpoint, Web service layers completely fulfill this need. But from a “human operator” viewpoint, the best results can only be obtained with teams of experts who master all three dimensions: Multiagent Systems, knowledge bases, and geospatial analysis. Interconnections between components and software, and between different software modules, are currently in an experimental stage, but already promise great results:

- GEAMAS-NG’s agents can be initialized by maps derived from either the cartographic module or ArcMap, in order to set up interconnection configurations (figure 18).
- IKBS’s knowledge bases can help GEAMAS-NG during specific simulations. During a simulation, if agents representing spaces should be generated, IKBS is able to determine the best consistency for the emergent taxa.
- ArcGIS’s algorithms can process spatial data from simulation results generated by GEAMAS-NG, and store maps for future use by policy-makers.

Figure 18: GEAMAS-NG is initialized and produces maps.
7. Results and discussion

Figure 19 shows the links between applications from downstream enhancement, on the one hand, and, on the other, software and services from the upstream enhancement of our IS. In the four-year period of the ETIC program between 2004 and 2007, we built fifteen applications, i.e., two product-services, corals\textsuperscript{17} and hydroids\textsuperscript{18}, nine prototypes and four mock-ups\textsuperscript{6}. The software IKBS and GEAMAS, which generate static and dynamic knowledge-based applications (Corals, Marine Turtles, BIOMAS) were already operational before the beginning of the program, but they have been improved thanks to user input from focus groups and questionnaires. To give an example, GEAMAS-NG was able to help experts in designing and exploiting simulation models (see section 5.1) by providing concepts and user-friendly interfaces\textsuperscript{32}.

The first component service to arrive was the Directory in 2006 because the first demand was naturally and logically to promote the researchers themselves, and give them editing rights.

![Figure 19: Instantiation of ETIC architecture in 2007](http://etic.univ-reunion.fr/flimber/)

In 2007, we implemented the biodiversity and multimedia transverse modules that showed the desire of researchers to share their metadata. The first cartography module called FLIMBER\textsuperscript{19} was made with Flash technology on ArcIMS, the

\textsuperscript{17}http://coraux.univ-reunion.fr/, visited on 09/29/2008
\textsuperscript{18}http://etic.univ-reunion.fr/hydroids/, visited on 09/29/2008
\textsuperscript{19}http://etic.univ-reunion.fr/flimber/, visited on 09/29/2008
Internet viewer of ArcGIS, but due to a lack of interactivity and map cover, it was replaced by a simple geolocation service made with the GoogleMaps API. This module was directly connected to the multimedia document manager (see figure 8 of section 4.2).

The objective of the IREMIA team is to integrate the different data and knowledge modules as a hub of Web Software and Component Services to satisfy their interoperability and also their openness to other biodiversity and landscape information systems. Indeed, interoperability and integration of databases are the innovative challenge of international initiatives such as GBIF\(^{20}\) on biodiversity, EDIT\(^{21}\) on taxonomy, INSPIRE\(^ {22}\) on cartography. These information management projects are complemented with international projects on education and pedagogy through identification services such as KeyToNature\(^ {23}\).

However, all these international projects are not sufficient if our goal is to create an IS that answers political, management and pedagogical questions on a regional and local level - one that becomes an Information Service (not only a System) for citizens of Reunion Island. The design of the Insular Tropical Environment Information System is based on a collaborative methodology between marine and terrestrial research and education producers, computer science and graphic design editors, as well as with enterprises and end-users. All these persons must meet together on a co-design platform, share a common vision, work together with some pleasure and constitute a community of practice. The Intranet portal made with SPIP was a good experience that prefigured Wikis as a virtual exchange space. Nevertheless, the success of each project depends on the motivation of the leader that has to spend time devoted to the animation and communication process of the future product-service. This task is the most challenging issue of knowledge management 2.0 in communities of practice, because if the first objective of managing people is resolved, the documents will follow more easily. The advent of web 2.0 tools in 2006 calls for the use of social networks to do intranet collaborative research work (CSCW or e-research), and to promote Internet collaborative public learning on a large scale (CSCL or e-learning) \cite{11}. This orientation will be the next ETIC strategy for building the community of e-researchers and e-learners that define e-services together for insular tropical environment management and education (figure 20).

\(^{23}\)http://www.keytonature.eu/, visited on 09/29/2008
8. Conclusion

Managing a commons is a very difficult and complex challenge, because the protection of our natural patrimony is the result of people's awareness and faith in their future. It is also the inherited responsibility of a society that reaches adulthood. The creation of the Reunion National Park in 2007 is a first step in this direction, because it was necessary to stop the uncontrolled development of anarchic and galloping urbanization. In order to truly preserve insular tropical environments, the decision help tools we have designed in our ETIC program will not be sufficient. Data and Knowledge management are preferably centered on users rather than on documents. This idea is derived from the organization 2.0 initiatives [34], also called the next enterprise that emphasizes trust, e-services and social networks. In fact, Information Systems must be replaced by Information Services in order to innovate - mostly by anticipating usages, and not only technologies. This is why we will name the next ETIC program Ne×Tic (New insular tropical environment and ICT), which will focus on the use of prototypes.

The ethics of our Ne×Tic program is to share services that combine the three dimensions of a sustainable development process: environmental energy, economic resources and social information (figure 20). Environmental energy is bipolar (+,-): it determines the movement of things in one way or another. For the future, people in our insular tropical environment have to decide either to go in a material direction (i.e., industrial, rational, economical and individualist) or to engage themselves in an immaterial direction (i.e., post-industrial, symbolic, social and collective). The first choice is focused on consumption; the second one exemplifies creativity and openness. Indeed, when we share a material good, it divides itself, whereas when we share an immaterial good, it multiplies itself [39]. The problem is that resources and energy are becoming rare on our small island. We may say that Reunion represents a laboratory of the finite world with its natural and
cultural diversity and beauty, but also its social difficulties. The equilibrium of a sustainable development model will not be possible without taking into account the ICT dimension, which is necessary to make connections between people in a social network. Information must be shared and discussed by citizens for them to participate in their future.

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References

Designing an IS for the Preservation of Insular Tropical Environment


