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Modelling forest fire risk change related to land cover change: an integrative approach

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Abstract: Forest fire risk evolves due to land cover change. Several processes are involved like forest extension on former agricultural land and discontinuous urbanisation process. The dynamic of the risk represent the interaction between this vulnerable zones land cover change and fuel zones (forest) spatial dynamic. In order to manage the risk through land planning, decision makers need simulation tools able to preview spatial evolution of risk levels.
To simulate the dynamic of the risk we chose an integrative way, consisting in integrating simulators specialised in either fuel land cover spatial dynamic (forest) or vulnerable land cover dynamic. While existing simulators of forest land dynamic were used, like Afforsim (Prevosto & al., 2003) at micro-local scale (patch) and Landis II (Scheller & al. 2006) at macro-local scale (landscape), two spatial dynamic models specialised in discontinuous urbanisation process and complex areas dynamic representation, Micropolis at micro-local scale, and Macropolis were specified and implemented into simulators. Micropolis is a Multi-Agents Based system where interact social agents and spatial agents. Macropolis is a cellular automata developed on a raster geoghaphical information system environement.
Then, a specific integration platform called Pyroxene was developed. Pyroxene is also a multi-agents system specialised in spatio-dynamic models and simulators integration. It is organised in an architecture inspired form HLA (High Level Architecture), and is partly compliant with the FIPA (Foundation for Intelligent Physical Agents) specification. It allows executing specified *models for model integration* on geographical system, in order to ensure semantic interoperability of the different models.

Keywords: ecosystem modelling, urban modelling,, model integration, multi-agent based system, high level architecture, land cover change, forest fire risk, geographical information system.

Introduction

In the context of global change, management of natural risks is one of the main stake decision makers have to face, at a wide range of scales, from local scale up to global scale. Vulnerability of human societies increases due to their spatial and demographic extension as well as to the extension of their ecological footprints. Natural risks, defined as the product of a natural hazard that cannot be controlled by human, on one hand, and a human vulnerability on the other hand, emerge from the interaction between processes related to both natural systems and human systems (Lampin, 2005).

Thus, in order to be able to assess natural risk and its evolving, representations of these two kinds of system are required. Models of these systems are produced by very different scientific disciplines and knowledge fields: natural sciences (ecology, geology, hydrology, climate science, etc.) for natural systems, social sciences (economy, human geography) for human systems. Therefore, building a full representation of risk requires integrating knowledge produced by at least two of these scientific disciplines. Whether the choice is to build a new integrated model, or to integrate existing models, the modeller has to specify the semantic relationships between both knowledge fields.

On a dynamic point of view, risk management activity is based on medium term planning. The use of dynamic models in order to simulate natural risk change is a key support for planning decision making. Because natural risks are commonly spatial, planning decision support for risk management is usually based on spatio-dynamic models integration.

Forest fire risk is a particular natural risk, mainly managed at a restricted range of local scale levels. It is closely related land cover, and in particular, the spatial relationship between fuel areas and vulnerable areas (Millington 2007). Modelling forest fire risk change is based on land cover change modelling.

In this paper, we propose a decision support tool to manage forest fire risk increase due to land cover changes, based on dynamic models and simulators integration. The proposed system is designed to integrate models referring to different knowledge fields, like forest ecosystems, urban dynamics and forest fire risk. It is also a "multi-scale" integration system, as it permits to integrate models describing the same territory at two different scale levels.

In section 1, a general presentation of forest fire risk change modelling based on thematic and scale integration of several disciplinary spatial models is proposed. In section 2, advantages of integrated modelling regarding models integration is discussed. In section 3, some land cover change models to be integrated in order to simulate risk change are described. In section 4, a conceptual framework of the integration system is presented, as well as a framework for the specification of models for model integration. In section 5, the implementation of this framework as an agent-based integration platform called PYROXENE is presented as well as an example of integrated simulation.

1. Relationship between land cover change and forest fire risk change

Forest fire risk change can be assessed at different time scales: daily, related to meteorological change, at seasonal scale, or at long term, related to climate and land cover change. Our aim is to represent the only long term risk change, for land management planning decision support.

1.1 A competition between two spatial processes on a shared spatial resource

Forest fire risk increase stems from the competition between two very different spatial dynamics: *fuel spaces* dynamics (forest ecosystems), and *vulnerable* spaces dynamics, in particular discontinuously urbanised territories (Jappiot *& al.*, 2000), in peri-urban areas. In the Mediterranean area, historical urban nucleus and forest patches where generally separated by cultivated agricultural lands. During the XXth century, agricultural land abandonment due to drift from the land, and forest economical uses limitation, led to forest extension on abandoned agricultural lands. On the other hand, urban spread became more and more discontinuous, due to new urbanisation policies.

When both processes meet on the same shared space, particular land cover appears, called "interface" areas. In such interface, fuel vegetal geographical objects like trees and shrubs are mixed with isolated buildings like individual houses (*Figure 1*). So interfaces are critical zones regarding forest fire risk.

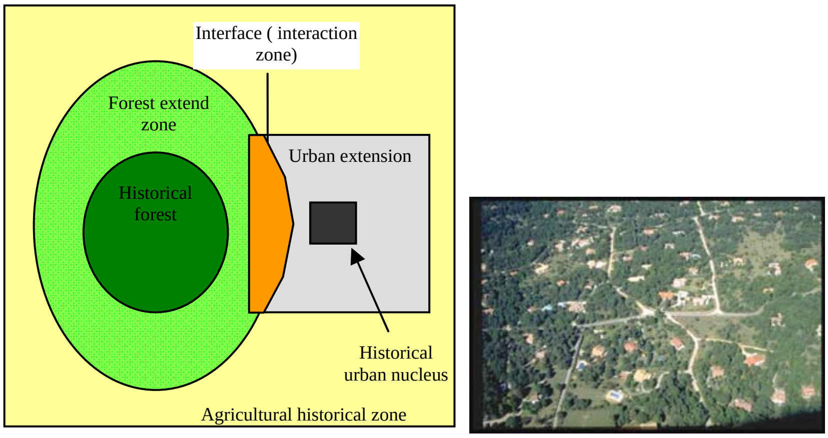

Figure 1. Formation process and an example of interface zones

Forest fire change is the result of interaction between these two main spatial processes "sharing" the same space. One efficient way to simulate risk evolution is to model separately these two processes and then to represent their interaction. The global scheme of the demarche is illustrated in *Figure 2.*

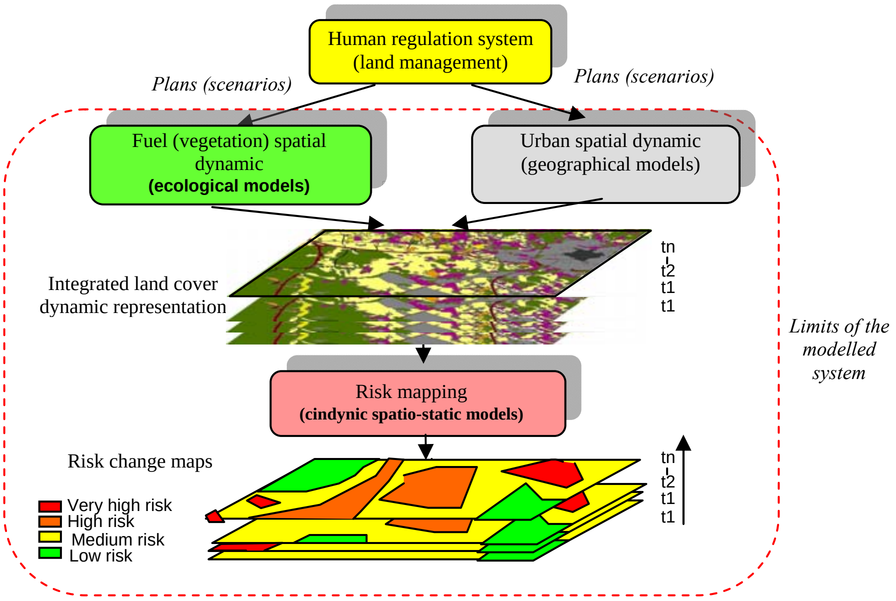

Figure 2. Integration of land cover change models to simulate risk evolutions

Fuel spatial dynamic can be represented by models produced by ecology, while urban spatial dynamic can be represented by dynamic models produced by urban geography. An integrated land cover map is produced by combining the maps produced by both models, at each step of time of the simulation. Land cover dynamic is so represented by a stack of dated integrated land cover maps.

On each of these maps, a risk model is applied in order to assess risk level at any point of the area. The risk model is a spatial static model, based on spatial analysis index calculation that permits to quantify the spatial relationship between fuel and vulnerable geographical objects. Calculated risk levels are then put into classes. Dynamic representation of risk levels is a stack of dated map of classed risk levels.

We call "thematic integration" the set of activities that are required to permit different models of different knowledge fields to interact and produce new information taking into account information produced by each theme.

In order to support spaces management planning decision-making, it is not required representing the social system of regulation decision-making itself. This social system is, in fact, the end user of or specified tool. The end user will elaborate and test different planning scenarios in order to assess their possible effect on the future risk levels map during the planned period.

1.2 Interfaces properties and scale transfer

Interface is a complex class of land cover where fuel and vulnerable geographical objects are mixed. It has got particular properties related to both its inherent risk and dynamic:

- Risk related to interface is closely linked to the spatial arrangements of its microscopic components (density, aggregation, distances between fuel and vulnerable objects, etc.)
- Dynamic of interfaces also depends on spatial arrangements of its atomic components. The reason is that behaviours of components of different classes interact. For example, buildings have a strong impact on surrounding trees installation and growth.

As a result, neither risk nor interface dynamic can be assessed using aggregated models at macroscopic scale level, while such models are usually sufficient to represent "pure" land cover classes risk and dynamic (forest, continuous urban zones, homogeneous agricultural zones, etc.). A scale transfer from macroscopic level to microscopic level has to be done locally. The scale transfer aims to "resolve" the interface in its microscopic components (*figure 3*).

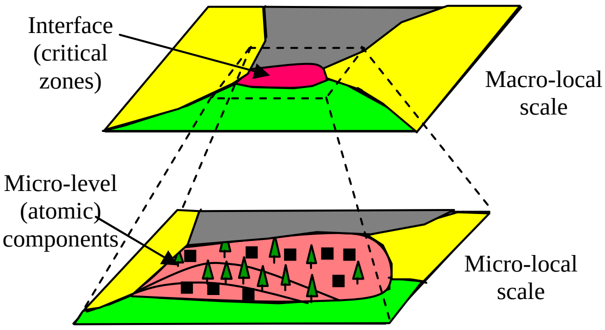

Figure 3. Scale transfer on interfaces areas

Scale transfer is based on usual aggregation/disaggregation procedures. New microscopic level models have to be used in order assess the dynamic and the risk inherent to interfaces, at microscopic level. Then, outputs of these models have to be integrated to macroscopic level. We call "scale integration" the set of activities that are required to permit different models of different scale levels to interact and produce new information taking into account information produced at each scale level.

1.3. Model integration for planning decision support

Different level of planning decision might be considered. In case of land management planning decision support for forest fire risk limitation, useful spatio-temporal scale range is comprised between macro-local scale, where operational planning decision are made, and micro-local scale, where strategic planning decision are made *(figure 4)*.

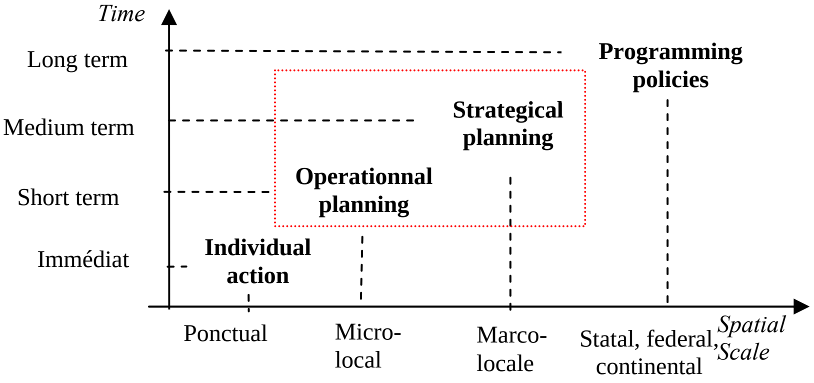

Figure 4. Planning decision level regarding spatio-temporal scale levels

A simulation based decision support tool for land management is used in a scenarios testing loop *(figure 5)*.

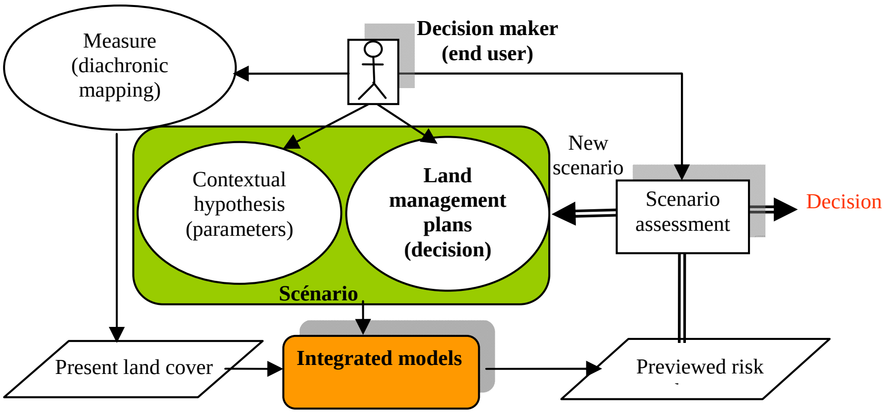

Figure 5. The scenarios testing loop

Scenarios have two main components: a set of parameters values representing hypothesis on the context evolution (climate and ecological parameters, socio-economic and demographic parameters, for example) on one hand, and a proposed management plan on the other hand. The scenario is simulated with the integrated models, using an initial state obtained by an experimental method of diachronic mapping. Results in terms of risk spatial evolution are assessed: the plan can be modified and re-tested if results don't satisfy the user, or the final planning decision can be made otherwise.

2. Integrated model versus models integration for risk change representation

The design of both thematic and scale integrations might be based on two opposite demarches: the first is to design a new complete integrated model; the second is to use existing models and to make them inter-operable. In this section, we compare these two possibilities in relation to our problematic.

2.1. Design of an integrated model

Trying to design one unique model of the global « humanised-ecosystem » is highly difficult first because of the complexity of such a global system, and secondly because the required knowledge is distributed in very different disciplines.

In order to simplify the integrated representation, it is possible to design a very much aggregated model that does not describe underlying thematic processes, but a global behaviour of the system. For instance, spatial cellular automata based models might be used to represent integrated land cover dynamic, without representing explicative underlying processes: only the neighbourhood relationship between cells is taken into account. Such models have poor explanation capabilities, but might be able to represent properly general spatial dynamics at some convenient scale levels. The limit of the approach might be reached if some specific processes or representations are required to answer the asked question at the demanded scale. In our application, particular dynamics of interfaces and discontinuous urbanisation process are not properly represented by purely spatial aggregated models, because the neighbourhood relationship is not the main factor of the dynamic.

Limit of the integrated approach also lays in the question of who design the global model. As nobody has got the whole knowledge required to design an integrated model, the design process requires necessarily a participative approach. Even so, representing the interaction between domains requires a certain rate of interdisciplinary knowledge that might be elaborated during the participative process.

Finally, such an integrated model might have difficulties to evolve. As soon as the designing group is ended, the model will stay at its initial release, without having possibilities to follow progress done in each scientific knowledge field.

2.2. Existing models integration

On the other hand, using existing models, already produced by the different scientific disciplines, requires an integration process. This approach permits to save modelling and developing efforts, and to always use the latest (supposed to be the best) thematic model produced by each discipline.

One first limit of this approach is that models are usually not designed to be integrated: they might not perfectly fit to answer the "integrated" question. Moreover, implemented models might be very difficult to make inter-operable, depending on their development paradigm, their information/data model, their developing language, their computing environment, etc.

Finally, integrating different models still requires representing information related to the interactions between initial thematic knowledge fields. As for integrated modelling, models integration must be based on participative approach, where different domains specialist can together elaborate the knowledge related to the interaction between the different knowledge fields.

In the case of forest fire risk modelling, the main argument of existing models reusing is that many elementary models, and in particular risk models, are still under construction. The models integration approach let the initial models evolving with their own cycle of life, and can even be changed if better new models are designed.

3. Initial models to be integrated

Three fields of thematic knowledge have to be formalised into operating models, and then integrated, in order to represent the risk dynamic: the forest ecosystem thematic (fuel zones dynamic), the discontinuous urbanisation thematic (vulnerable zones dynamics), and the forest fire risk thematic itself.

1.1. Forest fire risk

Forest fire risk assessment in relation to land cover is based on static spatial risk models, provided by risk sciences ("*cindynic*"). Four main approaches of forest fire risk modelling are considered (Maillé *& al.*, 2006):

- *Analytical attribute* risk modelling allows calculating the risk level $Risk_i$ at any geographical point *i*, in relation to the geographical attributes of this point (slope, vegetation etc.):

$$Risk_i = f(vegetationType_i, slope_i, aspect_i,...)$$

- *Aggregated spatial* risk modelling (or global approach) aims to assess the risk level at any geographical point, in relation to its neighbourhood.

$$Risk_i = f(aggregation_i, diversity_i, \Sigma_j\ distance(j,i), \Sigma_j\ interfaceLength(j,i),...)$$

- *Analytical spatial* risk modelling aims to assess the risk on one given geographical point, in relation to the ignition probabilities and the propagation possibilities in the environment of the point;

- $RS_k = \int_i (e_i * p_{ik})$

with

RS_k *risk in k ;*
e_i *: ignition probability in i ;*
p_{ik} *: propagation proba from i to k*

- Finally, *statistical risk modelling* is based on statistical study of multi-simulation results of forest fires, using specialised forest fire simulators.

All theses approaches lead to a risk level map related to a given territory. Models are implemented on *Geographical Information Systems*.

3.2. Forest ecosystems dynamic

Ecology provides models able to represent the vegetal dynamics at different scale levels. Many approaches are used that represent more or less physiological or phytosociological underlying processes (Coquillard *& al., 1997*). We distinguish two great families, regarding their scale of application:

Micro-local scale models are very often individual based models (Grimm, 1999) that aim to represent the "spatial behaviour" of vegetal individuals (like trees, patches, etc.) Examples of such models are AFFORSIM (Prevosto *& al.*, 2003) or CAPSIS (de Coligny, 2006). They are based on results of functional ecology that describe, in particular, the vegetal reproduction processes (seeds widespread, competition, etc.). They are usually applied to very small spatial extensions (forest patches).

Macro-local scale models are mainly based on knowledge provided by landscape ecology. Examples of such models are SIERRA (Mouillot *& al.*, 2001) or LANDIS II (Scheller *& al.*, 2006). They aim to represent the global behaviour of vegetal stands at "landscape" scale, and might be applied to larger spatial extends (whole forest massif, forest region, etc.).

3.3 Urban dynamics

Modelling vulnerable zones dynamic and urbanisation process is based on knowledge mainly produced by geographical sciences. Models are often formalised by cellular automata, in order to represent spatial diffusion processes, taking into account spatial attributes of the geographical space on which the diffusion occurs (Batty *& al.*, 2000, Dubos-Paillard *& al.*, 2003, Ellerkamp, 2001). Some of the social processes leading to land cover changes might also be represented in the simulation models (Napoléone, 2005), and then formalised using analytical, individual based, or mixed paradigms like for the CLUE model (Veldkamp 2001).

However, specific works on discontinuous urbanisation process and interface dynamic modelling, at local scale, are quite rare. We developed two models specialised in complex land cover dynamic representation at micro-local scale and macro-local scale respectively called MICROPOLIS and MACROPOLIS.

3.3.1 Modelling discontinuous urbanisation process: the MICROPOLIS Multi-Agents Based Model

The Multi-Agents Based System (MABS) MICROPOLIS, was specifically developed to represent the discontinuous urbanisation process into interfaces zones. It is a metaphor of the social system driving the formation process of spatial structures where built up geographical entities are mixed to fuel geographical entities. It aims to represent land owning transactions leading to individual houses settling in, onto wild lands that can be built-up.

At the initial step of time t0, the area is represented by two geographical information layers: one represents land cover; the other one represents land owning (cadastre). On this area operate five classes of *social agents* and two classes of *geographical agents*. Social agents represent human actors in the real world territory. Geographical agents are spatial agents (Rodriguez *et al.*, 2002) representing geographical objects of the real world territory.

Social agents and their main role are the following:

- The *"Land Manager"* agent has mainly a coordination role ;
- *"Land owner"* agents try to sell plots of land that usually can be built-up.
- *"Buyer"* agents negotiate with land-owners to buy suitable plots of land, and then usually build-up a house on.
- *"Land traders"* agents are possible intermediaries between land owners and buyers. They also cut into large patches to create little plots suitable for building.
- *"Geometer"* agents fix modalities and operate cut of large patches ordered by land traders or land owners. To do so, they coordinate geographical multi-agents sub-systems.

Geographical agents are organised into local sub-systems. They have in charge optimisation of spatial operation ordered by social agents (Geometer or Buyer). Geographical agents are of two classes:

- *Parcels agents* (there are several sub-classes) operate and optimize a spatial function they are implemented for. Some parcels agents try to optimize the shape of newly cut plots, by negotiating their shared border drawing. They also might optimize spatial structure by dissolution of their shared border (fusion of parcels) in order to reach a surface as close as possible from the building surface specified in the urbanisation plan rules.
- *Buildings agents*, optimise their geographical location in relation to other building location and specifications provided by the builder (who is either a *buyer* or a *land trader*).

During the simulation (*figure 6*), new spatial structures emerge from the different spatial processes, in particular patches cut and buildings settlement. At each step of time, these structures can be characterized using spatial analysis indexes (entities density, average inter-distance between entities of the different classes, for instance), in order to assess the risk evolution related to these structures. Its usual step of time is the mouth, and its usual simulation spatial extend range is comprised between 100 ha and 5000 ha (about the area of a French "commune", i.e. elementary administrative entity).

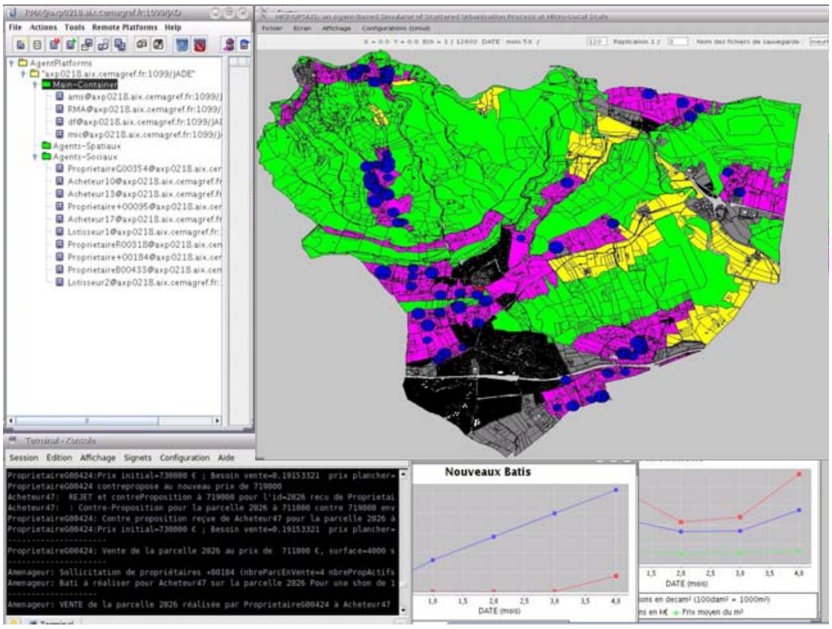

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Figure 6. A MICROPOLIS simulation session (blue disks are new buildings)

The prototype is developed in the JAVA© language, using the cognitive agents development platform *(API)* Tilab JADE©.

3.3.2 Complex land covers dynamic modelling at macro-local scale: the MACROPOLIS model

MACROPOLIS is a grid of cellular automata implemented on a raster Geographical Information System (GIS) environment. It is specialised in the representation of complex spaces dynamic, in particular *interface spaces*, where vegetal geographical objects (trees, copse, etc.) are mixed with human isolated buildings. Transition functions between the different states of the automaton cells, are based on the quantification of the spatial relationship between the different components of the *interfaces spaces*. The spatial relationship is assessed by raster spatial analysis indexes calculation *(figure 7).*

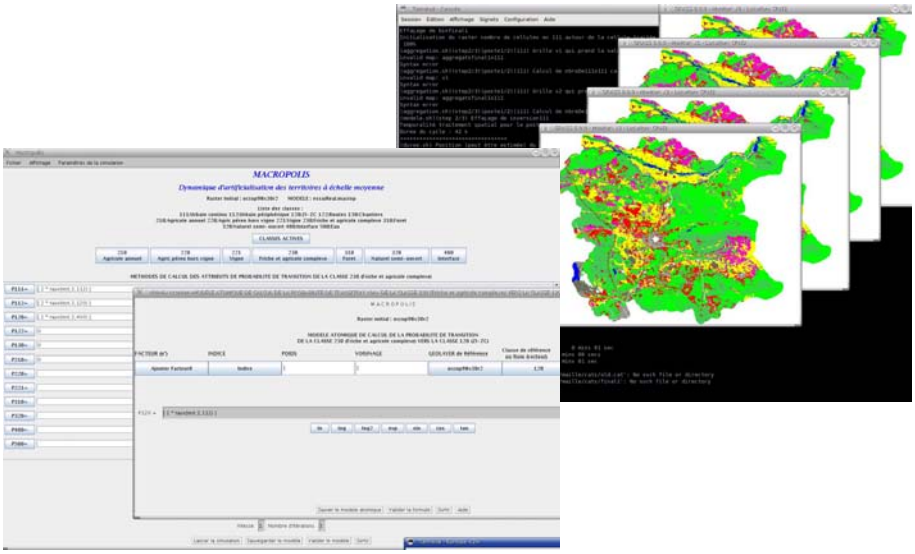

Figure 7. The MACROPOLIS configuration interface and a simulation session

Figure 7 shows the MACROPOLIS user graphical interface that permits to program different transition functions for each pair of land cover classes. The transition function might be based on raster spatial analysis index such as diversity (Shannon entropy index, for example), aggregation, interspersion, etc.

MACROPOLIS produces as output a stack of dated GIS raster layers, representing land cover at each step of time. Its usual step of time is the *year*, and its usual simulating spatial extend range is comprised between 10 000 ha and the extend of an average European "region".

MACROPOLIS is developed on the raster dominant GIS GRASS©, and endowed with a JAVA graphical user interface (GUI).

4. Conceptual approach of models integration

Models integrations require two main sets of specifications:

- The first requirement is to specify *semantic interaction* between knowledge fields the thematic models are based on. The aim of this specification is to make models “semantically consistent”, so that they are able to “understand” each others. To do so, we have first to organise the different models into a conceptual framework. Then we have to specify semantic relationships between the different concepts handled by each model. We call this first step of the integration the “conceptual” integration.
- The second step of the integration is the specification of the syntax relationships between implemented models and simulators. The aim is to make software modules interoperable. We call this second step “operational integration”.

In this section, we describe the general conceptual framework of the integration system as well as a specification framework of some "*integration models*" aiming to make the different models *semantically consistent*. In the last section 6, we’ll describe the paradigm and architecture of the integration system that was implemented to insure the interoperability between simulators and implemented risk models.

4.1. The general conceptual framework

Our purpose is to integrate six simulators, related to three themes and two scale levels. All are spatial models. Four are dynamic models and two are static.

The *figure 8* describes the general conceptual framework organising these different components. Between the component, **models for models integration** have to be specified, in order to make them “*semantically consistent*” and able to communicate in between them.

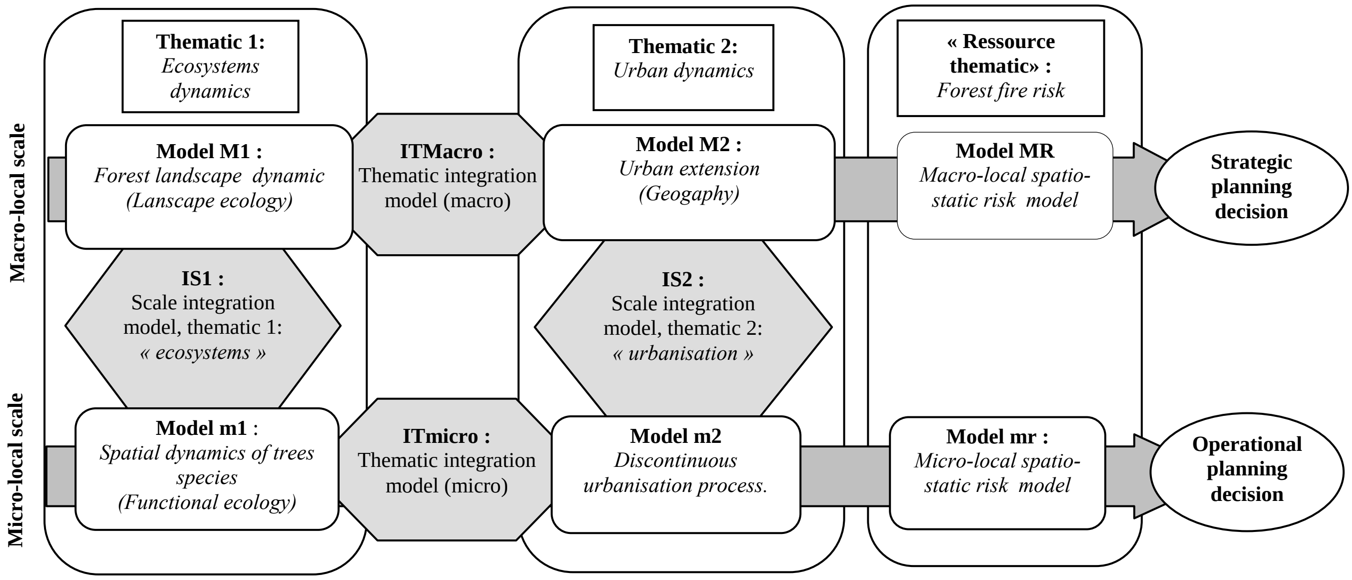

Figure 8. Conceptual framework for model integration

Four models for model integration have to be specified:

- Two models for thematic integration, i.e. one for each scale level (ITMacro and ITmicro).
- Two scale integration models i.e. one for each thematic (IS1 and IS2).

Models for models integration have to be specified by the expert user, within a specification framework proposed by the integration system. We describe this specification framework in the next sub-section.

4.2. The conceptual specification framework of models for models integration

A conceptual specification framework of models for models integration is proposed (Maillé, 2008). The framework first distinguish "thematic" integration specification, that concerns models at a same scale level, and scale integration specification, that concerns models operating at different scale levels. Scale integration specification can be considered as a complex thematic integration, including scale aspects.

For both thematic and scale integration specifications, the framework is structured in relation to the three *views* of the generic conceptual framework for *spatio-temporal* systems representation proposed D. Peuquet in 1994 (Peuquet, 1994), called the "*Peuquet triad*".

The three views of the Peuquet triad are the spatial view, the temporal view and the semantic view.

We first explain principles of thematic integration specification before giving elements on scale integration specification.

4.2.1. Thematic integration

The purpose of the specification framework is to permit the user to specify the result of spatial interactions between objects produced by sptio-dynamic models.

➔ *The semantic view* specifies the class of an entity resulting from the spatial interaction between an entity produced by model M1 and another entity produced by model M2 (*figure* 9).

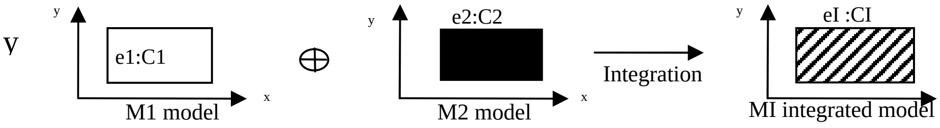

Figure 9. Example of an interaction between spatial objects produced by two models

For example, the specification of the semantic view for the integration of a model of ecosystem dynamic and a model of urban dynamic is formalised by a list of propositions relating the different classes handled by each model (*table 1*).

Model for models integration MI
(1) grassLand $\wedge_{MIEco}$ continuousUrban -> notActiveEco
grassLand $\wedge_{MIEco}$ discontinuousUrban - > grassLand
grassLand $\wedge_{MIEco}$ wildLand -> grassLand
grassLand $\wedge_{MIEco}$ notActiveUrb -> grassLand
bushyLand $\wedge_{MIEco}$ continuousUrban -> notActiveEco
bushyLand $\wedge_{MIEco}$ discontinuousUrban - > bushyLand
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Table 1. A partial example of the semantic view of thematic integration specification.

Conclusions of the propositions (i.e. the "outputs" of the integration model) are classes handled by the ecosystems model. This component of the model permits the integration of information produced by the urban model in the ecosystem model simulation. The opposite, i.e. the integration of information produced by the ecosystem model in the urban model simulation, have also to be specified by a list of propositions which conclusions are classes of the urban model.

➔ The specification of the *spatial view* describes how the spatial description of the entity resulting from the interaction is deduced from the spatial description of the interacting entities (**Erreur ! Source du renvoi introuvable.**).

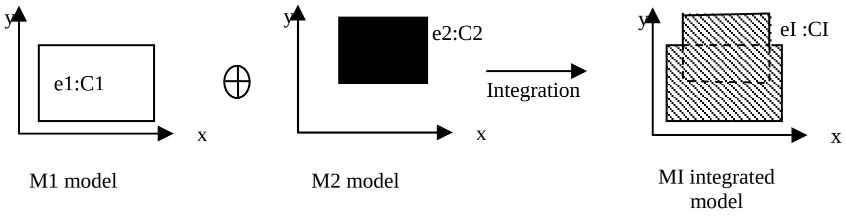


Figure 10. Specification of the spatial view

This specification is formalised by a particular spatial function. If initial entities are polygons, the function is usually the *intersection*. In the example of **Erreur ! Source du renvoi introuvable.**, the function is the *union* of the initial entities.

➔ Finally, the *temporal view* permits to distinguish an interacting entity, i.e. an entity newly created by on of the models, and an already existing "interacted" entity (*figure 11*). For example, if a *forest* is produced by an ecosystem model on to an existing *opened wild land* (urban model) the result is a forest. On the other hand, if an *opened wild land* is produced by an urban model (to prepare the future urbanisation, for example) on to an existing *forest* (handled by the ecosystem model) the result is an opened wild land.

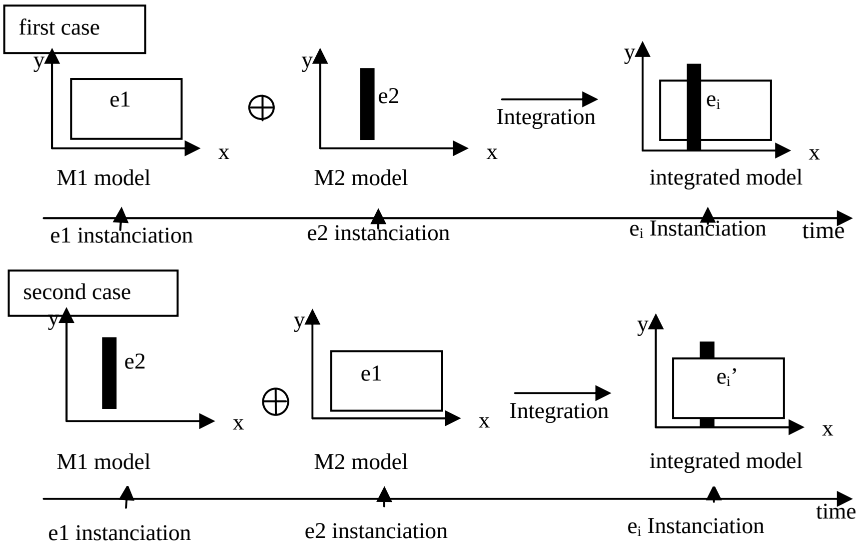


Figure 11. Graphical illustration of the temporal view on thematic integration

4.2.2. *Scale integration*

Scale integration specifies the interaction between entities handled by a macroscopic model and microscopic entities is it composed of, handled by a microscopic model. Specification of model for scale integration is based on usual aggregation function.

➔ *The semantic view* specifies the class of a macroscopic knowing the classes of the entities it is composed of (*figure 12*).

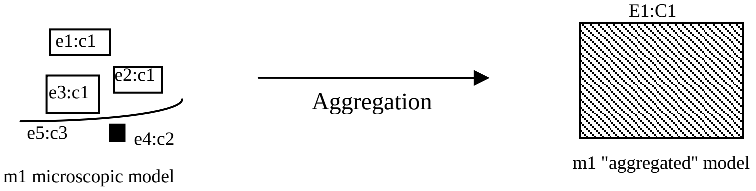


Figure 12. Graphical illustration of the semantic view of scale integration model

The specification is formalised by the definition of some attribute thresholds. For example, a macroscopic area might be considered as *Forest* (macroscopic level) if density of *Trees* (micro-level) overtakes a defined thresholds.

➔ *The spatial view* specifies the way to define spatial description of macroscopic entities, given the spatial description of the microscopic entities it is composed of (*figure 13*).

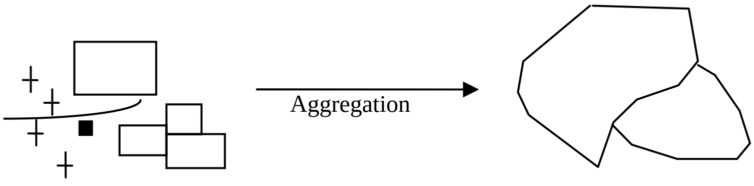


Figure 13. Graphical illustration of the spatial view of scale integration model

Formal models are mainly based on envelope curve determination algorithms.

➔ *The temporal view* on scale integration model aims to represent the interaction between *processes* running at different organisation levels. It assumes that a change event series at microscopic level might induce a change event at macroscopic level (*figure 14*).

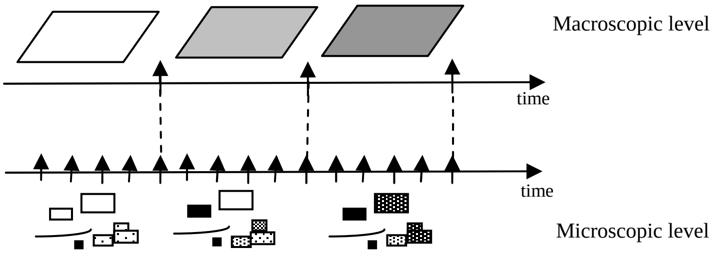


Figure14. Graphical illustration of the temporal view of scale integration model

This conceptual level aims mainly to solve semantic constraints of the integration of spatio-dynamic models. The operational integration, which permits the syntax interoperability between the different models is described in the following section 5.

5. Operational integration

We developed and integration system that aims to solve the whole syntax constraints to the simulators interoperability, in order to make them able to function together synchronously, and produce correct results.

The developed system, called *Pyroxene,* is a prototype of an integration platform of land cover change simulators for the simulation of forest fire risk change. The platform has a few notable specificities:

- It is a multi-agents based system (MABS), not directly dedicated to dynamic systems modelling (Bousquet, 2001), but to models integration (Ferber 1999). The platform is partly compliant with the FIPA (Foundation for Intelligent Physical Agents, FIPA, 2000) specification.
- It is a SOA-like (Service Oriented Architecture, Nickul 2005) distributed system, partly compliant to the High Level Architecture (HLA) specification (IEEE, 2000). It is composed of a central agent-based mediating infrastructure and some peripheral software modules supporting the different integration functions (Serment, 2007).
- Modules are existing implemented software (in particular model simulators) "wrapped" into particular wrappers agents, in order to integrate them into the MABS (*figure 15*).

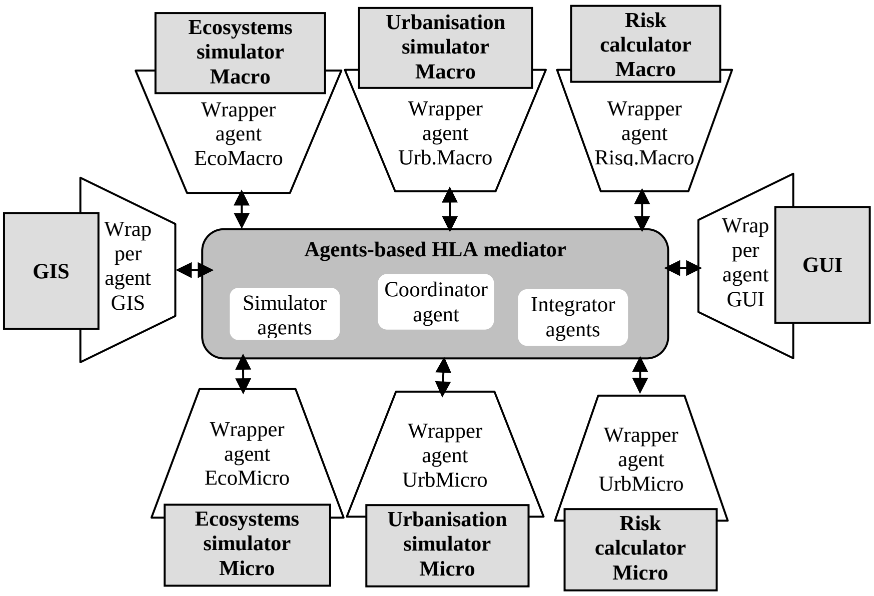


Figure 15. HLA-like architecture of the Pyroxene platform

- The integration process is based on the execution of thematic and scale integration *models* on Geographical Information Systems, either raster (GRASS, open source under GNU GPL licence) or vector (ESRI ArcGIS/ArcInfo Workstation). Modules (including simulators) process and exchange mainly GIS layers, while agents (including wrappers) exchange messages (*figure 16*).

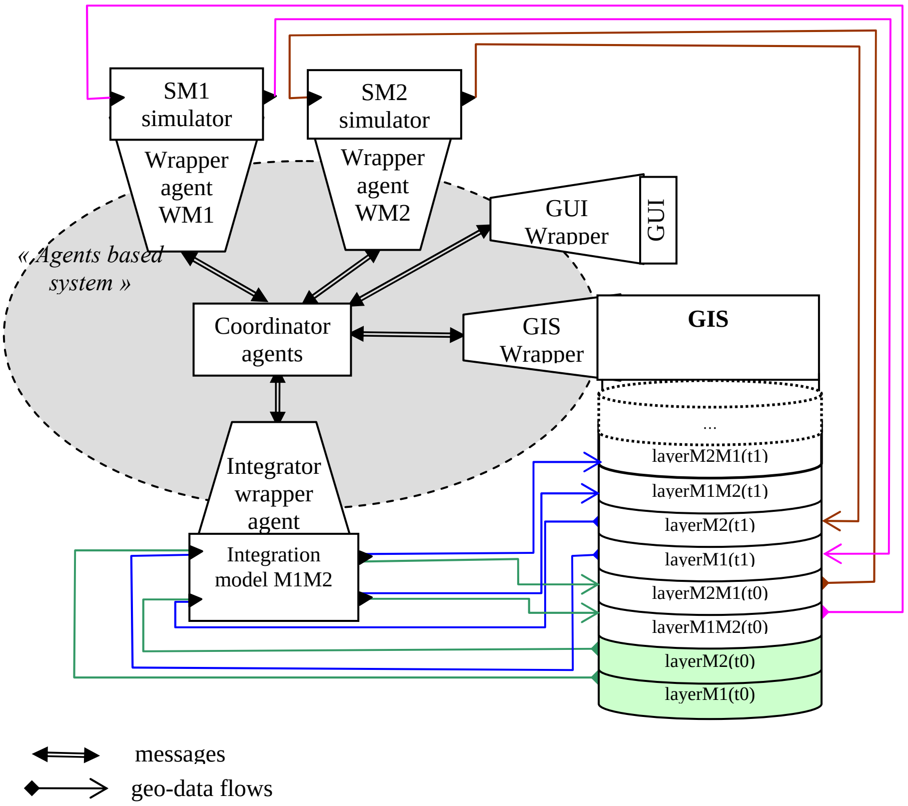


Figure 16. Messages and data flows during an integrated simulation

Figure 17 gives an example of messages exchange sequence during one step of an integrated simulation. The coordinator agent first asks to simulator wrappers a certain number of simulation steps (one step, if both models have the same time step duration). When it gets the two positive reports (success), it asks to an integrator agent to integrate the two GIS layers produced by the models. The integrator agent asks the GIS wrapper agent to execute the model for models integration. When it is done, the wrapper agents send back the report (success of failure) to the integrator agent that transmits it to the coordinator. If the integration was successful, this one asks the risk calculator agent to calculate the risk on the integrated GIS layer. To do so, the risk calculator agent asks the GIS wrapper agent to execute the risk model. As soon as the coordinator receives a positive report, it increments the integrated simulation time step and restarts the cycle.

Many other required tasks (data format conversion, data transportation, etc.) are also required and executed using different wrapped software modules.

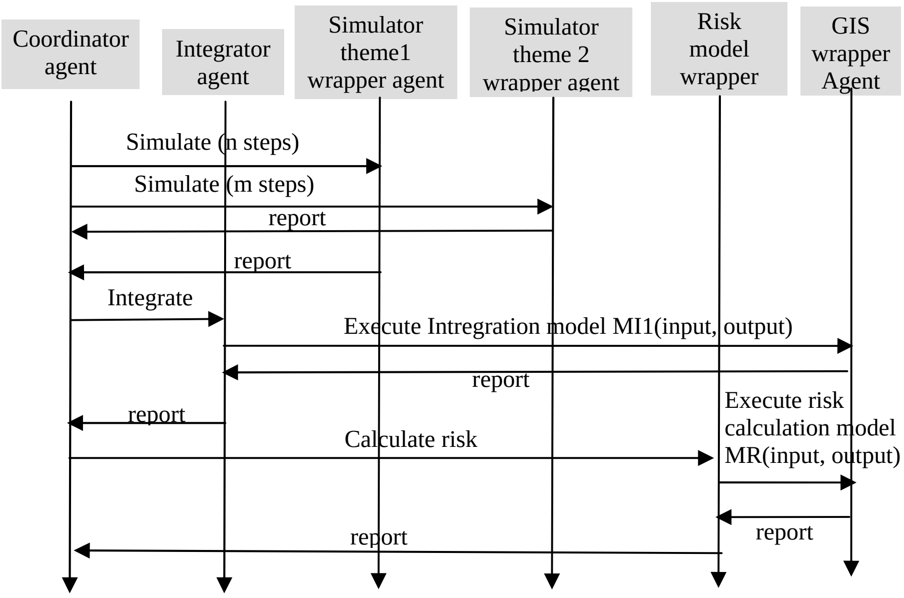
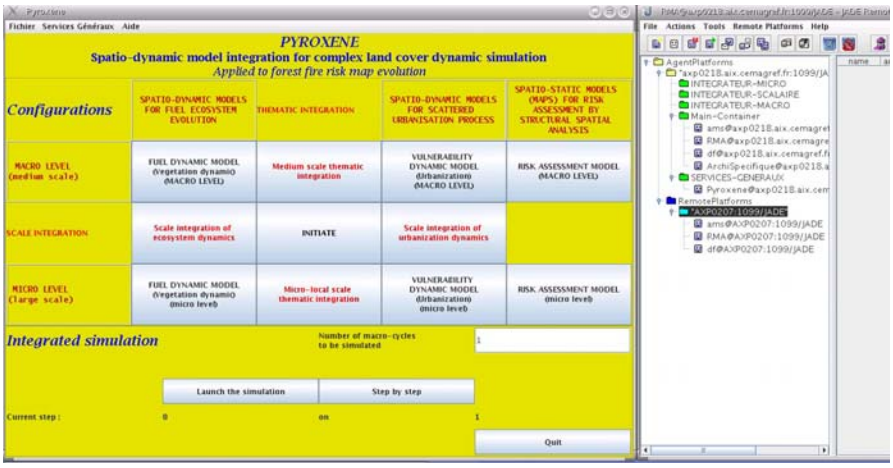


Figure 17. Example of message exchange sequence required for one step of integrated simulation

The implemented Pyroxene tool has got a fixed structure that permits to integrate three themes (ecosystem dynamics, urban dynamics, risk calculation) at two scale levels (micro-local et macro-local). It is developed in the JAVA© language, using the cognitive agents development platform *(API)* Tilab JADE© (*figure 18*).



PYROXENE
Spatio-dynamic model integration for complex land cover dynamic simulation
Applied to forest fire risk map evolution

Configurations	SPATIO-DYNAMIC MODELS FOR FUEL ECOSYSTEM EVOLUTION	THEMATIC INTEGRATION	SPATIO-DYNAMIC MODELS FOR SCATTERED URBANISATION PROCESS	SPATIO-STATIC MODELS (MAPS) FOR RISK ASSESSMENT BY STRUCTURAL SPATIAL ANALYSIS
MACRO LEVEL (medium scale)	FUEL DYNAMIC MODEL (Vegetation dynamic) (MACRO LEVEL)	Medium scale thematic integration	VULNERABILITY DYNAMIC MODEL (Urbanization) (MACRO LEVEL)	RISK ASSESSMENT MODEL (MACRO LEVEL)
SCALE INTEGRATION	Scale integration of ecosystem dynamics	INITIATE	Scale integration of urbanization dynamics	
MICRO LEVEL (large scale)	FUEL DYNAMIC MODEL (Vegetation dynamic) (micro level)	Micro-local scale thematic integration	VULNERABILITY DYNAMIC MODEL (Urbanization) (micro level)	RISK ASSESSMENT MODEL (micro level)

Integrated simulation

Number of macro-cycles to be simulated: 1

Current step : 0 on 1

```
AgentPlatforms
  "axp0218.aix.cemagref.fr:1099/JA
    INTEGRATEUR-MICRO
    INTEGRATEUR-SCALAIRE
    INTEGRATEUR-MACRO
    Main-Container
      ams@axp0218.aix.cemagref
      RMA@axp0218.aix.cemagre
      df@axp0218.aix.cemagref.f
      ArchiSpecifique@axp0218.a
    SERVICES-GENERAUX
      Pyroxene@axp0218.aix.cem
  RemotePlatforms
    "AXP0207:1099/JADE"
      ams@AXP0207:1099/JADE
      RMA@AXP0207:1099/JADE
      df@AXP0207:1099/JADE
```

Figure 18. The graphical user interface of the integration platform "Pyroxene"

Pyroxene is now tested on one experimental zone in the Aix-Marseille conurbation, gathering 43 "communes" (elementary administrative entities) of the "*Pays d'Aix Agglomeration Community*".

Figure 19 presents an example of a serial of dated risk level maps obtained by integrated simulation on the studied area (Maillé, 2009).

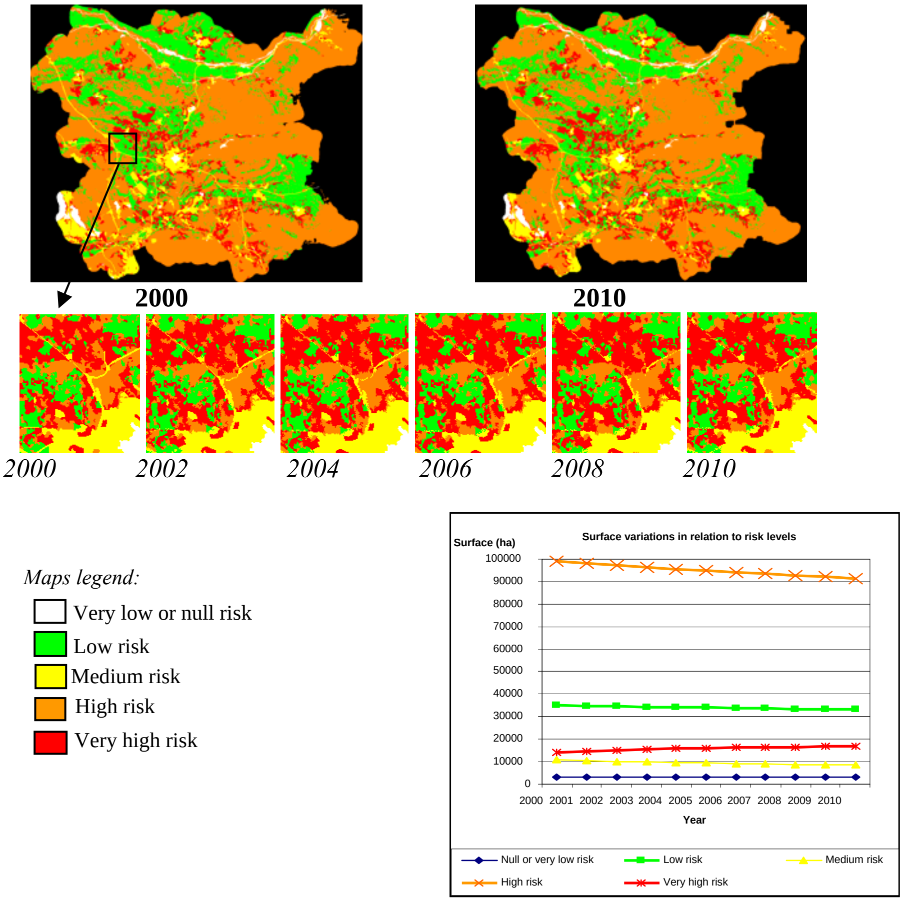


Figure 19. Example of integrated simulation of risk level change

The presented simulation example (*figure 19*) is limited to purely scale integration of two urbanisation oriented models of different scales: Macropolis and Micropolis. Both models have different time step values, so the figure represents ten Macropolis annual time steps (from 2000 to 2009) and one hundred and twenty Micropolis monthly time steps located on some critical interface zones.

The simulation previews a decrease of the *high risk* area (-8%), due to the limitation of pure forest surfaces, and an increase of the *very high risk* area (+19%), due to extension of isolated buildings into the forest (interfaces). *Low risk area* also decreases (-5%), because initially opened discontinuously urbanised areas (with low risk) get more and more vegetal fuel (trees, shrubs, etc), and so become *high risk* areas. *Medium risk* areas also decrease (-19%): these are often former agricultural areas consumed by both urbanisation phenomenon and forest advance phenomenon after abandonment. Finally, *very low or null risk* areas remain very stable (these are mainly continuous urban areas, neck soils, water surfaces, etc.).

Conclusion

Integrative approaches are very efficient in environmental risk change simulation for at least one key theoretical reason: risk is itself an integrative topic. Natural hazard is relevant to natural systems, while vulnerability is relevant to human systems. On the other hand, choosing to integrate existing models, rather than specifying a new integrated model is mainly justified by practical reasons: knowledge in each required discipline evolves, and so their produced models. Integrating existing simulators is certainly one of the easiest ways to guarantee the integrated model evolving.

We propose a platform for land cover simulators integration in order to represent forest fire risk change at local scale. Semantic integration is based on specification of models for models integration, while syntax interoperability of the different simulators is operated by a dedicated multi-agents based system (Wooldridge, 2002). Models for model integration are executed on a geographical information system (GIS).

We validated the viability of such a solution that produces consistent results. Although the system is quite resource consuming, it can be distributed on several computers in order to improve its performances. Confidence validation is however a long term task, based on ex-post diachronic mapping experimental works, in different contexts. One of the main difficulty for confidence validation is to separate the error due to initial models from the error due to the integration process. Moreover, validation of risk models is quite delicate because of the lack of experimentation possibilities.

Further work will first be related to knowledge field interaction formalisation for specification of models for models integration. Interactions between knowledge fields may be formalised using domain ontologies that would permit to easily identify the relationships between their concepts. As handled information is spatio-temporal, spatial ontologies (Vangenot, 2004) or spatio-temporal ontologies (Spaccapietra, 2004) should be used.

At the operational level, the platform should become more generic and be able to deal with any kind and number of spatio-dynamic simulators. This evolution will be based on the evolution of the publishing/subscribing service oriented architectures (Serment, 2007)

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