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Article *in* Procedia Computer Science · December 2017

DOI: 10.1016/j.procs.2017.05.090

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ScienceDirect

Procedia Computer Science 108C (2017) 968–977

Procedia Computer Science

International Conference on Computational Science, ICCS 2017, 12-14 June 2017, Zurich, Switzerland

A multi-world agent-based model working at several spatial and temporal scales for simulating complex geographic systems

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Abstract
Interest in the modelling and simulation of complex systems with processes occurring at several spatial and temporal scales is increasing, particularly in biological, historical and geographic studies. In this multi-scale modelling study, we propose a generic model to account for processes operating at several scales. In this approach, a 'world' corresponds to a complete and self-sufficient submodel with its own places, agents, spatial resolution and temporal scale. Represented worlds can be nested: a world (with new scales) may have a greater level of detail than the model at the next level up, making it possible to study phenomena with greater precision. This process can be reiterated, to create additional scales, with no formal limit. Worlds' simulations can be triggered simultaneously or in cascade. Within a world, agents can choose destinations in other worlds, to which they can travel using routes and inter-world 'gates'. Once they arrive in a destination world, the agents 'fit' the new scale. An agent in a given world can also perceive and interact with other agents, regardless of the world to which they belong, provided they are encompassed by its perception disc. We present and discuss an application of this model to the issue of the spread of black rats by means of commercial transportation in Senegal (West Africa).

Peer-review under responsibility of the scientific committee of the International Conference on Computational Science

Keywords: agent-based model, multi-scale, multi-world model, black rat spread, Senegal, simulation, gate

1 Introduction

Most natural and social systems can be characterised by different levels of organisation or abstraction, often consisting of heterogeneous entities of different kinds and sizes (Morvan, 2012). These constitutive (i.e., successively emergent) hierarchical systems (Gibson *et al*., 2000) can be studied by means of multi-level approaches (Fishwick, 1997). Furthermore, understanding the

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10.1016/j.procs.2017.05.090

processes performed by these systems within any given single level of abstraction may require the accurate representation and study of several spatial and temporal scales. This is particularly true for historical and geographic phenomena (Heppenstall *et al*., 2011). The colonisation of Senegal (West Africa) by the black rat is a typical example. The black rat is a commensal species known to disseminate using human transportation (Aplin *et al*., 2011). In this context, a simple model would represent the loading of rats onto commercial vehicles, followed by their transportation and unloading from those vehicles. Even within this parsimonious scheme, geographers and biologists discriminate, focus on, study and consider interactions between events occurring at different scales. For scientists studying this topic, the colonisation processes may include the dissemination of the species *(i)* over the whole country, over the scale of a century, by means of national transport routes (Lombard and Ninot, 2002), *(ii)* within regional districts, in which small roads and tracks form a dense network allowing the spread of this species to small sites over the scale of a decade (Lucaccioni *et al*., 2016), *(iii)* at the city or town scale, with rats able to spread on their own across the streetscape over the scale of a day. In such cases, multi-scale modelling can provide new insight into the functioning of such systems (Pumain, 2006).

Geographic modelling approaches are generally restricted to a certain spatial and temporal scale, characterised by an extension and a granularity (Langlois, 2009). In this work 'multiscale' refers to this possible navigation between several formalised spatial and temporal scales (e.g., Evans, 2012). We present a generic model that can account for the various scales simultaneously, together with the relationships between them. In our approach, a 'world' corresponds to a complete and autonomous submodel with its own fixed spatiotemporal scale, places, objects and agents. The formalised worlds can be nested: a world can represent a part of another world in greater detail, facilitating more precise studies of its phenomena. This process of moving between scales should be repeatable from one scale to another *ad infinitum*.

We first present the model selected to describe each autonomous world and the adaptation selected to tackle the multi-world multi-scale question. In this study, in addition to the design of agents and objects, we focus mostly on description of the spatial and temporal formalisms chosen to describe 'worlds' and the 'multi-world' system. We then present an application of this model to the particular case of the spread of black rats over historical time in Senegal. We then discuss this multi-scale approach in the context of previous works.

2 Presentation of the model

2.1 Spatial scale

Geographic space (the environment) consists of a Cartesian co-ordinate system determined by a metric and an extension. In our approach, space is formalised, in each autonomous world, as a combination of a continuous space conforming to its referential and a grid of given granularity where the cell size represents the spatial scale (Gibson *et al*., 2000; Vo *et al*., 2012). This granularity grid is set by the scientists studying the system, according to their perception of the phenomena studied at this scale. The discrete space provided by the grid makes it possible to

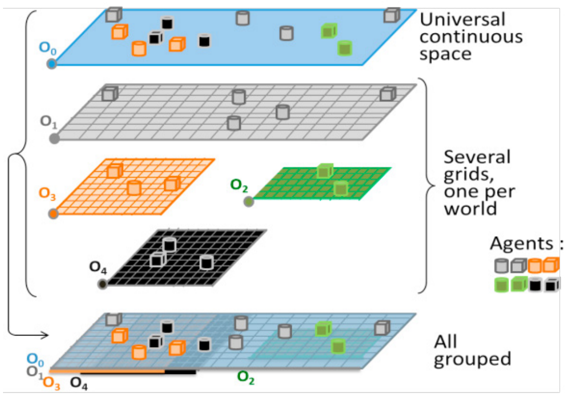

Figure 1: Architecture of the multi-scale spatial model. Each agent is referenced in the continuous space and in the grid of the world in which it stands. All grids belong to the same plane, that of the continuous space.

enrich the landscape with information from other sources and to identify higher-level structures (*i.e.*, patch of contiguous cells with the same characteristics). The combination of these different topologies makes it possible to locate precisely the neighbourhoods of points, objects and agents of the environment.

Within the multi-world model, the continuous space remains the ‘universal’ reference, and several grids of different granularities and extensions, each defining their own world, are embedded within this space. Each grid, representing the environment for a world, constitutes a discretisation of a geographic map representing part of the global domain to be studied (Figure 1).

2.2 Changing spatial scale

To take into account possible changes in spatial scale, agents must perceive their environment in a constant radius of perception (R), rather than in a single constant-order (N) Moore (or von Neumann) neighbourhood (Braga *et al.*, 2016). Thus, when changing spatial scale, the N value for the agents can be recalculated using $N = R / Cell\ Size$ (Figure 2).

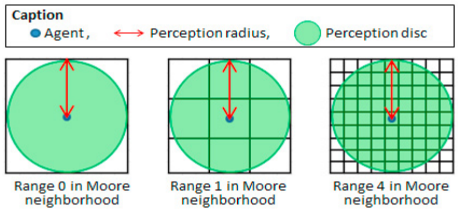

Figure 2: The number of cells that an agent can perceive depends on the size of the cells, when the perception radius of the agent is constant.

2.3 Time scale

The multi-agent model is a discrete timestep simulator controlled by a scheduler. For multi-agent modelling with discrete time scheduling, time scale is usually represented as the unique execution frequency of agents, and a multiple time scale model is the possibility to represent several schedulers in the same model (Vo *et al.*, 2012). In our model, agents in any one world can perform unitary actions programmed for a duration that may differ between agents (Guo and Tay, 2008). We define that duration, for each type of agent, as the ‘Activity Unit Duration’ (AUD). The time scale or granularity of a particular world is given by its own simulation step, referred to here as the ‘World Tick Duration’ (WTD).

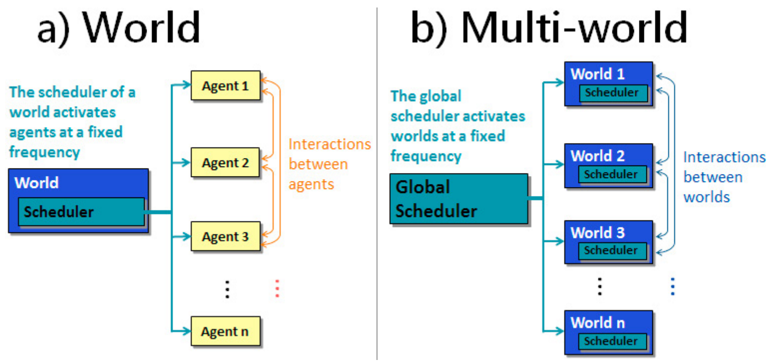

Figure 3: Execution of a world and of the multi-world model. Each single world model has its own scheduler, with its own temporal scale and execution frequencies for its agents. Multi-scale models include several worlds with different temporal scales managed by a global scheduler.

The world’s scheduler triggers the execution of the agents belonging to that world (Figure 3a), according to frequencies (F_i) calculated, for each type of agent, and updated, when WTD changes, as follows:

If WTD > AUD then F_i = WTD/AUD. In this case, agents execute their activity F_i times each WTD.
If WTD < AUD then F_i = AUD/WTD. In this case, agents execute their activity once every F_i WTDs.

Within a multi-world context, multiple time scales are managed by a higher-level scheduler known as the ‘global scheduler’ (Figure 3b). This scheduler has an overall time step characterised by a ‘global tick duration’ (GTD), which is the absolute time scale or reference scale.

Just as single-world schedulers trigger their agents' activities according to F_i, so the global scheduler successively activates the worlds it manages according to their own frequencies (F_j). F_j is calculated and updated, when a WTD or GTD changes, as follows:

If GTD > WTD, then F_j = GTD / WTD. In this case, single worlds are activated F_j times each GTD.

If GTD < WTD, then F_j = WTD / GTD. In this case, single worlds are activated once every F_j GTDs.

The frequencies F_i and F_j may not always be integers, and can therefore take a value of 1.33, for example. However, since time is discretised, agents or worlds therefore cannot be activated 1.33 times each tick, or 1 time each 1.33 ticks. This problem has been overcome by multiplying F_i or F_j by a convenient (*e.g.,* determined by scientists working in the field) order of magnitude. In the example given, a factor of 10 would result in agents or worlds being activated 13 times every 10 ticks or 10 times every 13 ticks.

2.4 Inter-world communication via 'gates'

Agents may sometimes have to travel to other worlds to reach specific places. This would be the case, for example, for a commercial transport vehicle carrying agents over using road networks (Mboup *et al*., 2015) We have facilitated the switch from one world to another in our model, by introducing the notion of 'gates' as compulsory crossing points common to several worlds (Figure 4).

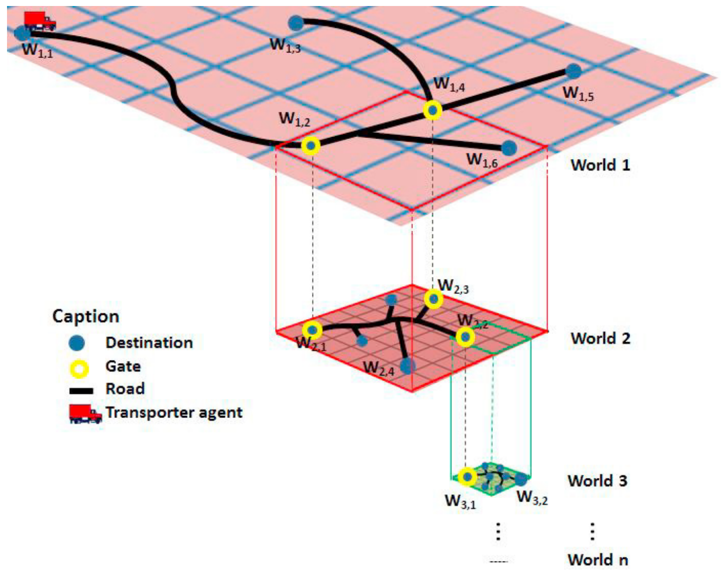

Figure 4: Use of crossing points between worlds. World 1 contains an area (red) that needs to be studied in more detail, represented by world 2, which itself contains a more detailed area, represented by world 3. For the red truck to reach its destination, $W_{3,2}$, a multi-world graph must be constructed, including gates to allow the truck to move bidirectionally between "world i" and "world j" (see the text for an explanation).

A gate is a cell that corresponds to another cell, of the same type, in another world. In the example of human carriers using the graph to move, the agent makes use of its 'knowledge' about the simulated worlds to build a graph covering several worlds to reach its destination. In this example, we assume an agent has to go from point $W_{1,1}$ in world 1 to point $W_{3,2}$ in world 3. The agent will travel along the shortest path, using the following steps, to reach its destination: it builds a "path of worlds" indicating the path to follow, {W_2, W_3}. The agent in W_1 must go to W_2 and then to W_3 before it can reach the point $W_{3,2}$. It must thus successively cross two worlds {W_2, W_3}. For each world in this path (e.g. W_2), it selects the most suitable gate to reach the world concerned (gate $W_{1,2}$), finds the correct (shortest) path between its current position and this gate, $W_{1,1}$ and $W_{1,2}$, giving {$W_{1,1}$ ... $W_{1,2}$}. At the gate ($W_{1,2}$), the agent leaves its current world and enters the other world (world 2), reaching the arrival cell ($W_{2,1}$) connected to the gate.

When an agent changes world, it sheds its set of references as well as those of the other agents and objects it contains. It thereafter adopts the references of the new worlds and let its embarked agents and objects do the same. For agents with time-dependent units of activity, speed must therefore be recalculated relative to the tick duration of the new world. The agent then adapts to the new spatial scale. For example, it retrieves, from the arrival cell, the type of graph that it can use. It goes through the whole process again when it moves on to the next world (W_3). If the world path is exhausted, that is, when the agent arrives in the world (W_3) containing its final destination ($W_{3,2}$), it develops and travels along the most appropriate (shortest) path between its current position ($W_{3,1}$) and its final destination ($W_{3,2}$).

2.5 Perception of multiple worlds by agents

As the worlds intersect spatially and agents can move between worlds, an agent in a given place in a given world must be able to perceive the objects and agents around it, regardless of the world to which they belong. In our implementation, this is achieved with the Moore neighborhood restricted to the perception disc of the agent, which is calculated precisely using the continuous space (Figure 2). Each time a new world is added to the model, and for each cell defining a place common to several worlds, the list of corresponding cells in the other worlds is updated. This method is somewhat cumbersome, but it makes it possible to define an extended Moore neighbourhood that can be intersected with the perception disc of the agent.

2.6 General implementation

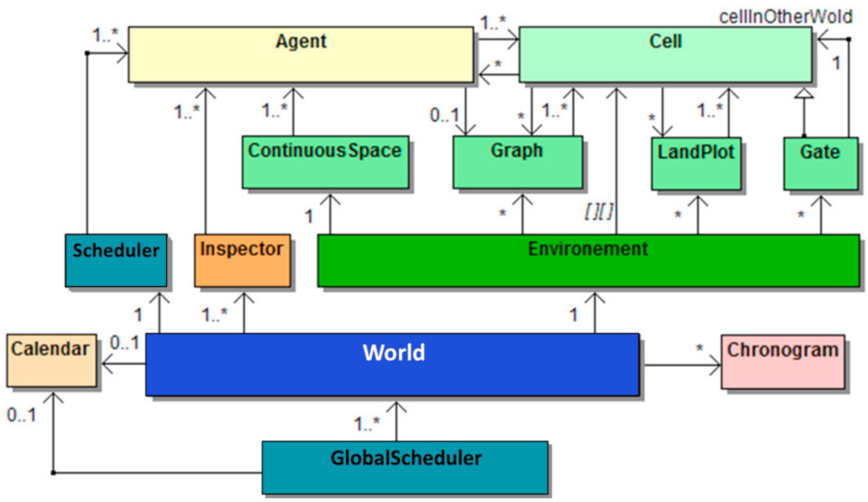

Figure 5 : UML-based class diagram of the generic multi-scale time-space model.

This scheme was implemented in Java thanks to the Repast Simphony platform (North *et al.*, 2013). The principal classes comprising its architecture are presented in Figure 5.

The world class is a general context associated with:

- One or several chronograms providing the historical succession of external events modifying the world.
- A calendar used to obtain and assert the current date and to convert time units.
- A scheduler that manages seasons or the arrival of new external updates from the chronogram. The scheduler object asynchronously triggers the specific activity of each agent within the world.
- One or more inspectors constituting an epiphytic system (Pachet *et al.*, 1994). Each inspector is responsible for retrieving and recording outputs from a simulation,

- A single landscape. A landscape is a global container referencing all visible objets. It is composed of three types of projections: a continuous space supporting the co-ordinate system and metrics; a set of graphs of different types used to move agents according to their type (trucks on roads, trains on rail, boats on rivers) and a raster for discretising the same space into contiguous square cells. Each cell is used to describe the 'soil' attributes (field, road, house, etc.). Patches of contiguous cells of the same type are identified as land plots. This class allows the delimitation and identification of different areas of the environment (cities, trade area, etc.).
- Agents of different types immersed within the continuous space and belonging to the cells of the raster. Agents execute patterns of behaviour according to a classical perception-deliberation-decision-execution process adapted from (Ferber, 1999).
- Each world can be simulated as a standalone model. In a multi-world context, different worlds are managed by an object of the GlobalScheduler class. This object has its own list of worlds created from the world class, manages the different time scales and triggers its worlds according to their time scales (see Figure 3).

3 Case study

The model was applied in an operational context in collaboration with biology and geography experts. It was used to investigate the process of black rat dispersal throughout Senegal by means of commercial transportation. Black rats were first reported in Senegal in the city of Saint-Louis and associated colonial settlements in the 19th century (Konečnỳ *et al.* 2013). They then made use of commercial transport activities to spread to the interior of the country, beginning with the northern waterways of Senegal. This species then progressively colonised the groundnut trade basin by means of the railway, which was being extended eastward from the coast. Most commercial transport is by road nowadays, and there has been an eastward extension of tarmac roads towards the region of Tambacounda and Kédougou.

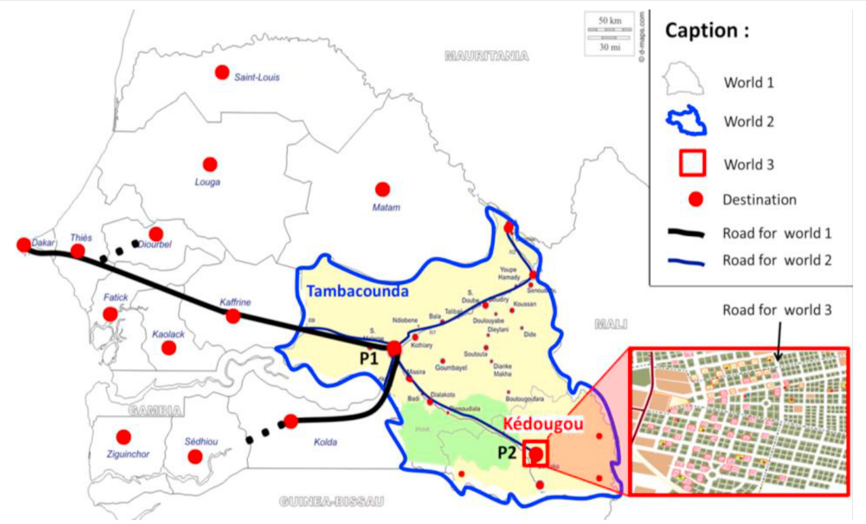

Figure 6: Localization and spatial extension of the three levels of abstraction (worlds) considered for the case study of black rat spread in Senegal.

The objective defined by the scientists working on this project was to set up a simulator to make it possible to represent and study the history of black rat dispersal in Senegal at the scales they were conducting their research and including changes (development of the groundnut trade basin, emergence of new cities, new transport routes, etc.) considered of importance for the processes studied. Three different spatial and temporal scales were thus designed and linked (Figure 6).

The 'centennial' scale (world 1) considers processes over the course of a century, with a daily step for the whole national territory digitised into square cells of 7.5 x 7.5 km; The 'decennial' scale (world

2) was a magnification providing a more thorough study of the regions of Tambacounda and Kédougou digitised into square cells of 2 x 2 km and simulated over 10 years (beginning in 1990), with an hourly step. The third scale focused on the city of Kédougou. This 'urban' scale (world 3) bore a raster representing the streets and districts of the city, with square cells of 38 x 38 m and one-minute time steps. A single level of the process was considered at all three scales: the loading of black rats onto commercial vehicles, their transportation and release from these vehicles. We first extended the model by adding the classes framed in red on Figure 7.

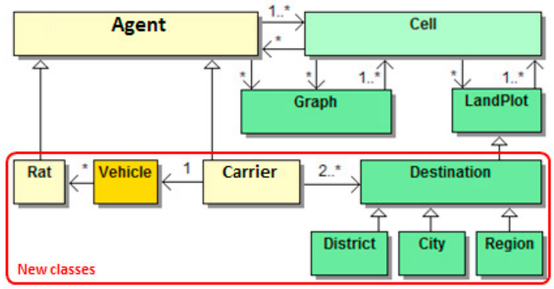

Figure 7: Extended model from Figure 5 adapted for the case study of the spread of the black rat in Senegal.

We considered black rats and the humans transporting them (referred to here as 'carriers') as the two types of agent in this model. The carrier agents can travel to a list of destinations that may be regions, cities, or districts, and have the use of one vehicle, of the truck, train or boat type. Each type of vehicle has its own speed and can travel along a particular type of thoroughfare (road, rail or river), corresponding to an instance of both the Graph and LandPlot classes. In this model, the black rat agents perceive their surroundings according to a given perception disc. They try to load with a given probability if a vehicle is located within their surroundings. Black rats are also biological entities; they grow in a succession of maturation stages, and they tentatively mate with their own relatives when they come across them. At a given time step and for a given world, the carriers select a destination and move towards it, whilst the black rats consider their surroundings and either try to board the vehicles or interact with other rats to reproduce.

The simulated space for each world was documented using the grid cells, each filled with information concerning the suitability of the environment for rats (bioclimates), the types of terrain (road, rail, river, city, etc.), the local population or the occurrence of particular items (gold mines, warehouses, etc.). Objects of the LandPlot class were used to delimit and identify the various different areas making up the environment (fields, trade areas, tracks, etc.). The graphs connect the landplots of a given type and establish transport routes. Gates were also included, for travel between worlds.

Each world was first designed and documented on its own, with different data sources for different worlds. This standalone approach was the principal mode of use of the model by scientists, and its outputs were discussed in detail.

4 Results

Using the model, we were able to represent the three scales, each with its own environment, scale and display, simultaneously (Figure 8). The yellow circles on Figure 8 represent the gates between worlds. The red trucks can travel between worlds via these gates, whereas the blue trucks, boats and trains are restricted to a single world. Vehicles can cross the areas represented in the other worlds without entering these other worlds. For example, the train travelling between Dakar and Kayes (light grey line) does not need to enter world 2.

Despite their representation on separate displays, the worlds are hence spatially and temporally nested and are located in the corresponding positions in the continuous space. It is possible to zoom in/zoom out of each display, and to superimpose displays, to improve observation of the passage between worlds.

The example on Figure 9 illustrates the differences obtained between a mono-scale model (centennial) and a cascading two scales (centennial/decenal) model. In this example, only black rat transportation by trucks was considered and other sources of variation such as the human population in cities or reproduction rate of rodents were disabled.

Simulation results are figured over 3 years with a temporal granularity of 6 hours for centennial and 2 hours for decenal. The truck fleet consists of 100 distinct agents traveling any city of both worlds in the case of the multi-scale model and any city of the centennial world for the single-scale one. Trucks going to the Kédougou central market, a place that is already referenced in the centennial world, do not enter the decenal world, whereas those going to the peripheral districts must enter it to reach their destination. Truck journey histories differ between the two simulations. Given these variations, the comparison of the cumulative result of the black rats transported in the multi-scale scenario presents a response curve which is of the same order of magnitude as that obtained with a mono-scale one.

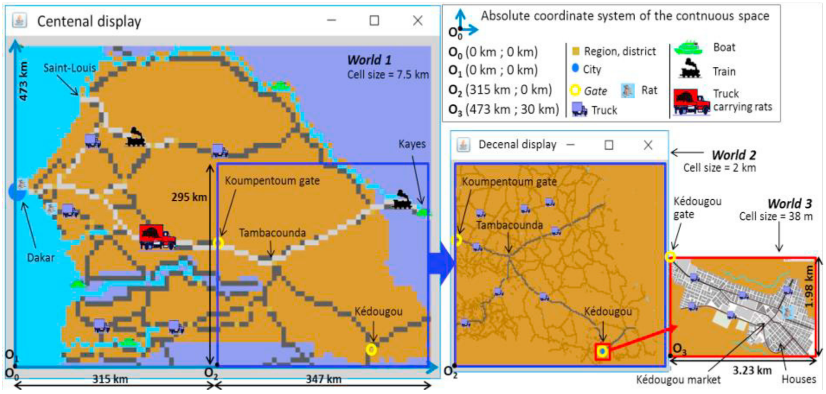

Figure 8: Simultaneous displays for a multi-world simulation. A red truck arriving on a gate leaves its current world to enter its destination world. The number of agents considered has been considerably decreased for the sake of clarity.

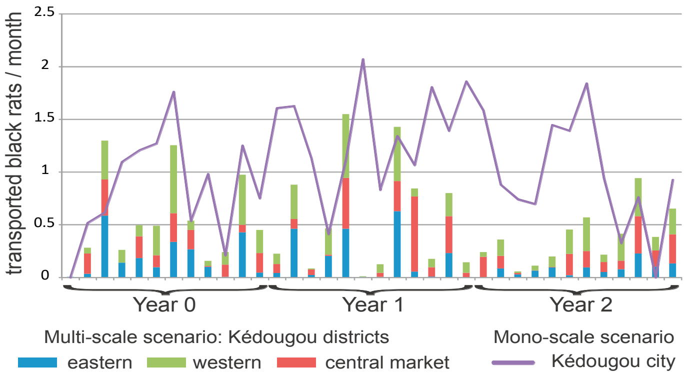

Figure 9: Comparison of the number of transported rats in the city of Kédougou using *(i)* a single-scale simulation where the city is a single entity and *(ii)* a two-world (centennial/decenal) simulation for which the city is divided into two peripheral districts and a central market. Reported values are averages obtained out of 50 separate runs.

5 Discussion

The approach used made it possible to simulate a cascading set of worlds of increasing spatiotemporal resolution for the exploration of phenomena occurring over several historical and geographic scales, in the case of the spread of black rats in Senegal. Comparison of simulations from a mono-scale world and a two-scale world shows an agreement between the order of magnitude of the transport dynamics of black rats obtained in both situations. However, in a multi-scale context, calibration and sensitivity analyses of the mono-scale models to parameters have to be called into question and should be reworked in light of the new offered perspectives.

Alternative approaches could be used to address the various questions tackled in this model. Another suitable approach for the nesting of the worlds would have been the recursive agent method (Vo *et al.*, 2012), in which an agent can itself be a complete model, with an environment, a scheduler and other agents. Several other methods have also been proposed for the passage between worlds, including 'capture/release' (*ibid*), 'emergence/group creation' (Servat *et al*., 1998) or 'aggregation/disaggregation' (Soyez *et al*., 2012), a method allowing individuals from one level to aggregate or disintegrate to another level (dynamic change of level).

However, these methods were developed principally for multi-level modelling of complex systems embedded within constitutive (i.e., successively emergent) hierarchies, whereas the proposed model was designed in a context of multi-scale modelling. Therefore, it seemed most appropriate to break the problem down into two steps: *(i)* make use of a classical agent-based submodel (world), in which each world is scale-specific and self-sufficient, an approach considered convenient for the scientists from different disciplines working on the problem at particular scales and *(ii)* include supplementary mechanisms to manage the interaction between worlds, such as passages between worlds via a 'gate' concept, and the perception of the multiple worlds by the agents. This decoupling makes it possible to reproduce agent management at world level (see Figure 3), such that any number of worlds can be integrated.

For multiple time scale modelling, we could have made use of the discrete event scheduling approach (Guo and Tay, 2008). This approach facilitates the non-uniform scheduling of the execution of agent activities when these activities occur over a diverse range of time scales. Our approach, based on discrete time scheduling, was chosen because it was considered more practical, as it is widely used in available simulation platforms, such as NetLogo (Wilensky, 1999), GAMA (Taillandier *et al*., 2012) or Repast (North *et al*., 2013) We completed this formalism with the appropriate algorithm, facilitating the integrated execution of worlds with different time scales, and of processing agents with different activity unit durations.

6 Conclusion

The proposed approach provides the necessary and sufficient mechanisms for simulating agents' moves between worlds defined at different spatial and temporal scales and, theoretically, without any formal limitation of the number of space-time scales. The cascade simulations that result from this approach lead to dynamics that are comparable to those of equivalent worlds considered at a single spatial and temporal scale. Building a model on these bases may provide geographers, biologists, etc. a useful tool for better identifying the most relevant scales, or combinations of scales, needed to understand deemed patterns of interest for their research questions.

Acknowledgment

This work was performed within the framework of the Chancira project "Environmental changes, goods and people movements: from invasion of reservoirs to emergence of human diseases: case study of the black rat in the Senegal-Mali boundaries", of the French National Research Agency, project no. ANR-11-CEPL-010. The authors wish to thank Laurent Granjon and Julie Sappa for their help during the revision process.

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