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

Pape Adama Mboup[1,2], Karim Konaté[1] and Jean Le Fur[3]

[1]*Département de mathématiques et d'informatique, UCAD/18522 Dakar Sénégal.*
[2]*UMR 022 BIOPASS, Campus de Bel-Air, BP 1386, Dakar, CP 18524, Sénégal.*
[3]*Institut de Recherche pour le Développement (IRD), Centre de Biologie pour la Gestion des Populations (CBGP), Campus Baillarguet, CS 30016, F-34988 Montferrier-sur-Lez, France.*
papeadama.mboup@ucad.edu.sn, karim.konate@ucad.edu.sn, jean.lefur@ird.fr

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).

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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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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

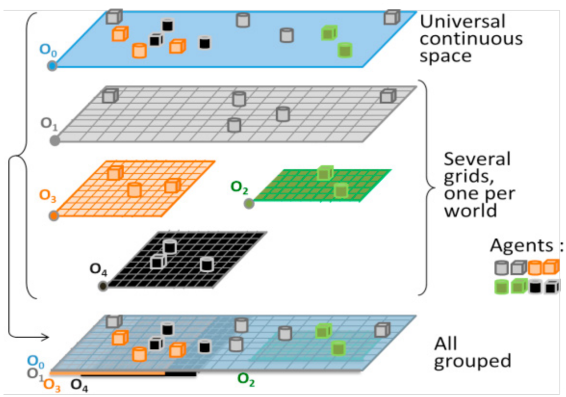

Figure 1: Architecture of the multi-scale spatial model. Each agent is referenced in the continuous space and in the grid of the world in which it stands. All grids belong to the same plane, that of the continuous space.

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