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**DYNAMIC NEIGHBORHOODS: A CONCEPTUAL  
MODEL AND ITS IMPLEMENTATION FOR SPATIAL  
DYNAMICS IN GEOGRAPHIC MODELING**

Raian Vargas Maretto

Master Thesis at Post Graduation  
Course applied in Remote Sensing,  
advised by Drs. Antônio Miguel  
Vieira Monteiro, and Tiago Garcia  
de Senna Carneiro, approved in De-  
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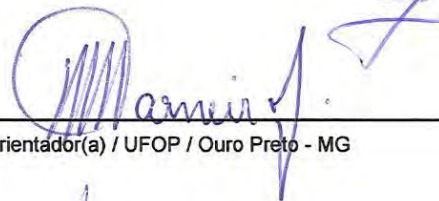
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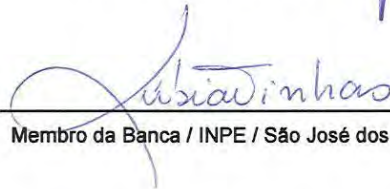
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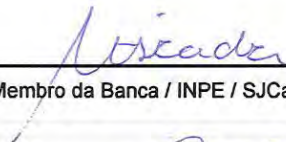
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*“É melhor atirar-se à luta em busca de dias melhores,  
mesmo correndo o risco de perder tudo,  
do que permanecer estático como os pobres de espírito,  
que não lutam, mas também não vencem,  
que não conhecem a dor da derrota,  
mas não tem a glória de ressurgir dos escombros.  
Esses pobres de espírito, ao final da jornada na Terra,  
não agradecem a Deus por terem vivido,  
mas desculpam-se ante Ele por terem  
simplesmente passado pela vida”.*

Bob Marley



*À minha família,  
Eliomar Maretto,  
Marize Vargas Maretto e  
Luan Vargas Maretto.*





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## ABSTRACT

Neighborhood configuration has a direct influence over the simulated output of Cellular Automata based models. In real world, spatial relations are not static, but changes over time. A dynamic model which aims to reproduce real world patterns needs to reflect these dynamics. This dissertation proposes a conceptual model, making use of an algebraic formalism that defines a set of operations for dealing with neighborhood structures that change over time, during simulation processes. It is an important feature for modeling experiments that aim to incorporate the natural complexity of many geographic phenomena. A computational implementation of the model has been provided. The Dynamic Neighborhood conceptualization was implemented as a new feature of TerraME (Terra Modeling Environment), an open platform for spatially explicit CA-based modeling and simulation. The implementation has extended the platform functionalities to cope with a new class of problems, where the dynamics involved implies on neighborhood structures that change over time, needing a runtime reconfiguration. A deforestation model has been developed using the Dynamic Neighborhood extension provided in TerraME to simulate the evolving deforestation patterns in the Xingú-Iriri frontier, at the south of Pará state, in the Brazilian Amazon. This model has been developed as a *proof-of-concept* to demonstrate the potential of the Dynamic Neighborhoods concept proposed, formalized and implemented in this dissertation for dealing with geographic modeling of spatial relations that change over time and, by doing so, they redraw its neighborhood definition along the simulation life cycle.

# VIZINHANÇAS DINÂMICAS: UM MODELO CONCEITUAL E SUA IMPLEMENTAÇÃO PARA DINÂMICAS ESPACIAIS EM MODELAGEM GEOGRÁFICA

## RESUMO

A configuração de estruturas de vizinhança exerce uma influência direta nos resultados gerados por modelos baseados em Autômatos Celulares. No mundo real, relações espaciais entre objetos não são estáticas, elas mudam ao longo do tempo. Um modelo dinâmico que objetive reproduzir padrões do mundo real deve refletir estas dinâmicas. Este trabalho propõe uma definição conceitual, através de um formalismo algébrico, de um conjunto de operações que permitem que ambientes computacionais destinados a modelagem dinâmica espacialmente explícita possam incorporar mecanismos para tratar vizinhanças que se alteram ao longo do tempo, durante processos de simulação. Esta característica é muito importante para experimentos de modelagem que objetivem incorporar a complexidade natural de muitos fenômenos geográficos. O modelo conceitual de Vizinhanças Dinâmicas foi implementado e incorporado ao TerraME (Terra Modeling Environment), uma plataforma livre para desenvolvimento e simulação de modelos dinâmicos espacialmente explícitos baseados em Autômatos Celulares. Esta implementação ampliou as funcionalidades da plataforma, de forma a possibilitá-la lidar com uma nova classe de problemas, cujas dinâmicas envolvidas implicam em estruturas de vizinhança que se alterem ao longo do tempo, precisando assim, serem alteradas em tempo de execução durante as simulações. Um modelo de desmatamento foi desenvolvido utilizando-se a extensão para tratamento de Vizinhanças Dinâmicas, implementada em TerraME. Neste modelo, foi simulada a evolução dos padrões de desmatamento na frente de ocupação do Xingú-Iriri, no sul do estado do Pará. Este modelo foi desenvolvido como um experimento de *prova de conceito*, a fim de demonstrar o potencial dos conceitos de Vizinhanças Dinâmicas, propostos, formalizados e implementados neste trabalho, para lidar com a modelagem de relações espaciais que se alteram ao longo do tempo e com isto, re-configurar suas definições de vizinhanças durante o ciclo de vida do modelo.

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## 1. INTRODUCTION

Over the 1970's, a series of research projects on several Geography departments was established based on a systemic view of the urban phenomena. A real city should be properly characterized not only by its fixed infrastructure components. The spatial distribution of different land uses competing, cooperating through interactions and depending on a *neighborhood* definition, established by a spatial proximity criterion, was a more realistic view. Spatial complex dynamics instead of static spatial relations started to be the research focus. This research line has been since then, very influential over the past years. The main instrument devised to investigate these complex spatial dynamics was the use of computer modeling and simulation. It would provide an empirical *test bed* for geographers, urban planners, architects, city engineers, sociologists, and others the like to investigate their theoretical hypotheses and conceptual models of the structure and functioning of urban systems and cities.

Almost at the same time, on the theoretical debate in the Geography field on representational perspectives for the geographic spaces, the ideas of a cellular geography (TOBLER, 1979) and cellular worlds (COUCLELIS, 1985, 1991, 1997) took shape. On the other hand, the use of 2D (two-dimensional) *Cellular Automata* (CA) computational structures in modeling and simulation of complex dynamics in physics and chemistry had already a long tradition. After the widely adopted view for the geographic space based on *cells*, computer CA-based models started to being used to provide the mechanism for observing urban systems dynamics. Most of the works presented on the related literature have followed this line from the 1990's until nowadays. It proved that the potential of *Cellular Automata* based models for urban dynamics studies had become widely recognized (BATTY; XIE, 1994; BATTY, 2000; BATTY, 2005; DEADMAN et al., 1993; PHIPPS; LANGLOIS 1997; WHITE; ENGELEN, 1993, 1994, 1997; WHITE et al., 1998; WAGNER, 1997; ALMEIDA et al., 2003a, 2003b, 2005, 2007; CLARKE et al., 1997; CLARKE; GAYDOS, 1998; O'SULLIVAN; TORRENS, 2000; VANCHERI et al, 2008).

In CA-based models, the *neighborhood* definition is a recognized key modeling component, because it determines how the geographic objects that build up the model interact among them (HAGOORT et al., 2008). It determines how the cells, which

represent the geographic objects, are spatially related. If two cells are considered neighbors of each other, it means that one is exerting some sort of influence over the spatial, temporal and/or behavioral state of the other. Each neighborhood relation also brings with it a way of value and differentiate that particular linkage. Usually, this is translated into a weight mapping definition. Thus, the weight represents the strength of the bounds that link those neighbors engaged during the model execution.

Dynamic models aim to represent complex dynamics of real world geographic phenomena. In real world situations, neighborhoods relations rarely keep their structure over time. Several studies have demonstrated that the CA-based dynamical models are sensitive to the neighborhood configuration. Ménard and Marceau (2005) and Kocabas and Dragicevic (2006) have demonstrated that their land use and urban growth model are sensitive to different cell resolutions and neighborhood configurations. Hagoort et al (2008) have investigated the impact of using neighborhood rules which are defined and calibrated on an *ad hoc* basis by trial and error methods, and that do not evolve along the model life cycle, on the simulated output of CA-based models.

In an attempt to avoid the problems raised by the use of fixed neighborhoods strategy, a small number of works have been developed more recently. The most recent is the work developed by Moreno et al. (2009), in which the authors present an implementation of a *dynamic neighborhoods* scheme in a vector-based cellular automata model (VecGCA) (MORENO et al., 2008). In their proposal, two objects are neighbors if they are adjacent or separated by other objects in which their states are favorable to the transition of states between them. In this approach, when the objects change their states, the neighborhood structures are reconfigured. However, this approach is tightly connected to the very specific CA extension they are proposing, the Vector Based Geographic Cellular Automata (VecGCA) (MORENO et al., 2008). It either does not allow for building neighborhoods structures based on the cells attributes or spatial relations than adjacency.

To overcome the problems raised by the use of fixed neighborhoods structures, i. e., neighborhoods that cannot be reconfigured at runtime in Dynamic CA-based models, this work proposes a formal model for providing runtime reconfiguration of neighborhood structures in CA-based modeling frameworks. It allows modelers to include neighborhood reconfiguration strategies in their modeling experiments. The

concepts developed, were implemented in TerraME (Terra Modeling Environment) framework ([www.terrame.org](http://www.terrame.org)). TerraME is a computer platform that implements the Nested Cellular Automata model (CARNEIRO, 2006), a CA extension proposed to allow the representation of complex dynamic phenomena through multiple scales. In order to demonstrate the concepts proposed and test its implementation, a deforestation model that needs the *Dynamic Neighborhoods* concept was developed. Based on Amaral et al. (2006), we simulate the evolving deforestation patterns in the Xingú-Iriri frontier, south of Pará State, in the Brazilian Amazon. It is important to notice that the main focus of this deforestation model in this work is not to reproduce exactly the real deforestation patterns, but demonstrate the potential of the *Dynamic Neighborhoods* concepts by verifying its impacts in a model developed based on empirical data over a real world setting.

### **1.1. Aims and Contributions of this work**

This work focus on creating the computational basis for providing runtime reconfiguration of neighborhood structures in CA-based computational modeling frameworks designed to cope with geographic phenomena. The conceptual model developed allows modelers to deal with neighborhood reconfiguration strategies as part of their model experiment. In order to do so we propose:

- (1) A typology of modeling situations where a neighborhood structure reconfiguration at runtime is a requirement from a modeler's perspective. It establishes three categories of changes for the neighborhood structure over models life cycle: (a) Endogenous Change, (b) Exogenous Change, and (c) Hybrid Changes.
- (2) A conceptual model for defining neighborhood structures that change over time based on an algebraic specification that makes use of graph-like structures. This model provides the basis for defining a set of operators (functions) to deal with the problem of allowing truly *Dynamic Neighborhood* structures to CA-based computational environments.
- (3) In order to evaluate the concepts proposed in (1) and (2), an implementation was provided for the **TerraME** (Terra Modeling Environment) platform

(CARNEIRO, 2006), an extended CA-based computational framework for spatial dynamic modeling and simulation.

- (4) A deforestation model that needs the *Dynamic Neighborhoods* concept was developed as a *proof-of-concept* experiment. We simulate the evolving deforestation patterns in the Xingú-Iriri frontier, south of Pará state, in the Brazilian Amazon. This model was based on Amaral et al. (2006), that describes the patterns of deforestation and the corresponding evolution of the transportation networks in that region.

## **1.2. This work and INPE's Research Agenda on Computational Platforms for Environmental Modeling and Simulation**

INPE have been studying the Amazon rainforest, monitoring and measuring its deforestation rates since the 1980's. Recently, the interest for studying the human actions in this region has increased considerably. At INPE, the GEOMA project (<http://www.geoma.lncc.br/>) has set up engagements beyond the Measuring-and-Monitoring scope and extended the internal research into the complete cycle of Measuring-Monitoring-Modeling-and-Simulating. The main goal is to build integrated computational models that can reproduce, at multiple scales, and based on empirical data and hypotheses about the process, the dynamics of this region. These models should be understood as a computational tool for testing and exploring hypotheses on the dynamics of the social and natural systems of the region.

In a joint effort between INPE and UFOP<sup>1</sup> (Federal University of Ouro Preto – MG), the **TerraME** platform has been developed to model and simulate spatial dynamic phenomena at multiple scales. This platform aims to provide the computational support for institutional projects, and other studies which intend to use spatial dynamic modeling as an empirical instrument for exploring complex dynamic systems. Through the implementation of the *dynamic neighborhoods* capability in this platform, these studies have a computer platform that can offer more flexibility for modelers. In this way, this work expands the universe of problems which can be tackled with the **TerraME** platform.

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<sup>1</sup> Universidade Federal de Ouro Preto (in portuguese).

### **1.3. Outline of the work**

This proposal is organized in five chapters. In Chapter 2, we present and analyze, from the literature, the closest related works. In Chapter 3, we describe in detail our proposal. In Chapter 4, we describe the deforestation model that is used here as a *proof-of-concept* experiment. And in Chapter 5, some concluding remarks are presented.



## 2. RELATED WORKS

Over the recent years, a series of CA-based computational models for dealing with complex spatial phenomena has been proposed in the literature. Some of them have advanced and have also proposed computational frameworks for effectively accomplishing modeling and simulation of these phenomena. All of them acknowledge the importance of the problem of the neighborhood structures definition from a modeler's perspective. Five of these proposed models are presented and commented here, with a particular emphasis on the specific ways they deal with the modeling of the neighborhood structures.

### 2.1. Layered CA model

Straatman et al. (2001) have proposed the Layered-CA model, in an attempt to deal with multi-scale dynamic models. It is composed by an iterative refinement of 2-dimensional cellular automata, in a set of connected layers. Every cell in a certain layer can have one parent in the higher layer and an arbitrary number of child cells in the lower layer, and it composes a vertical neighborhood. It assumes that all layers cover the same area. Figure 2.1 shows this structure, which is similar to a quadtree (FINKEL; BENTLEY, 1974), and allows embedding multiple models operating in different spatial resolutions.

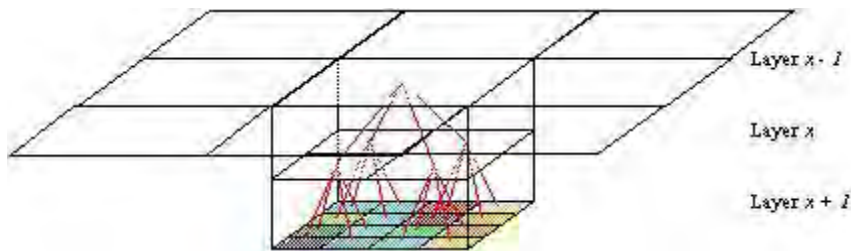


Figure 2.1 – Layered-CA structure, with vertical neighborhood relations.  
Source: STRAATMAN et al. (2001)

#### 2.1.1. Neighborhood definitions in Layered CA

There are two types of neighborhoods in the Layered-CA model, horizontal neighborhoods and vertical ones. The vertical neighborhoods are composed by the parents and children of the cells in a given layer. The horizontal neighborhoods can be defined by simply boundary conditions, and the neighbors of a cell are the immediately adjacent cells. If a selective refinement is made, as shown in Figure 2.2, all the refined



cells can have from 1 to 8 horizontal neighbors. The state of a given cell depends on both, its vertical and horizontal neighbors.

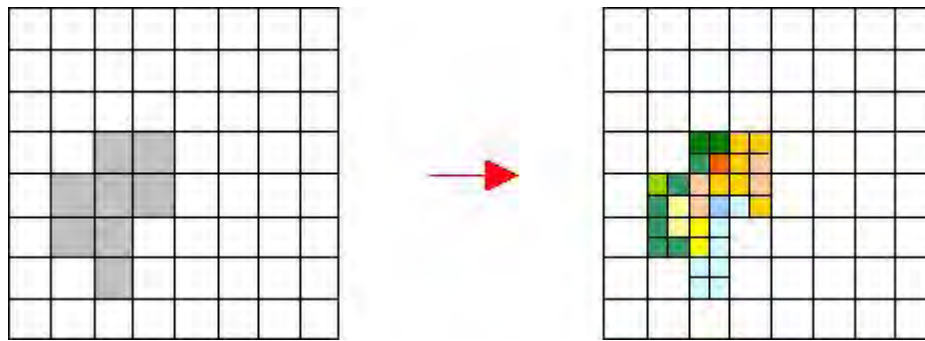


Figure 2.2 – Selective refinement in Layered-CA, where each cell have different numbers of horizontal neighbors.  
Source: STRAATMAN et al. (2001)

## 2.2. The DINAMICA model

The DINAMICA model was initially presented for simulation of Amazonian landscape dynamics (SOARES-FILHO et al., 2002; RODRIGUES et al., 2007). Basically, it is a CA-based model that presents multi-scale vicinity-based transitional functions, incorporating the spatial feedback approach to a stochastic multi-step simulation engine. The calculation of the spatial dynamic transition probabilities can be done mainly by the application of logistic regression. The main input for DINAMICA is a *landscape map*<sup>2</sup>, as well as selected spatial variables structured in two cartographic subsets according to their dynamic or static nature. The outputs are simulated landscape maps (one for each time step), spatial transition probability maps, which depict the probability of a cell at a position  $(x, y)$  to change from state  $i$  to state  $j$  (being  $i$  and  $j$  types of land-use and land-cover class), and dynamic spatial variable maps. Figure 2.3 shows a flowchart of DINAMICA operation.

DINAMICA works in various phases, and changes the transition rates according to a parameter called *Saturation Value*. The transition rates are passed as a fixed parameter within a given phase, and handled by the model when necessary during different dynamic phases. The calculation of the amount of cells to be changed in a given iteration is done by multiplying the number of cells of each land-use and land-cover class, occurring in a time step, by the transition rate. The *saturation value* forces the

<sup>2</sup> Land use and/or land cover map obtained from digital classification of orbital and/or airborne remote sensing images, or from GIS techniques.

stopping of the transition  $i - j$  when the number of cells in state  $j$  reaches a maximum quantity.

The spatial transition probabilities are calculated for each cell and for each specified transition through a polytomous logistic model. Logistic regression is used to depict the probability of a cell to change to one of the states, chosen along the line of the transition matrix. This procedure results in a set of maps depicting the probability of a cell to change to another state.

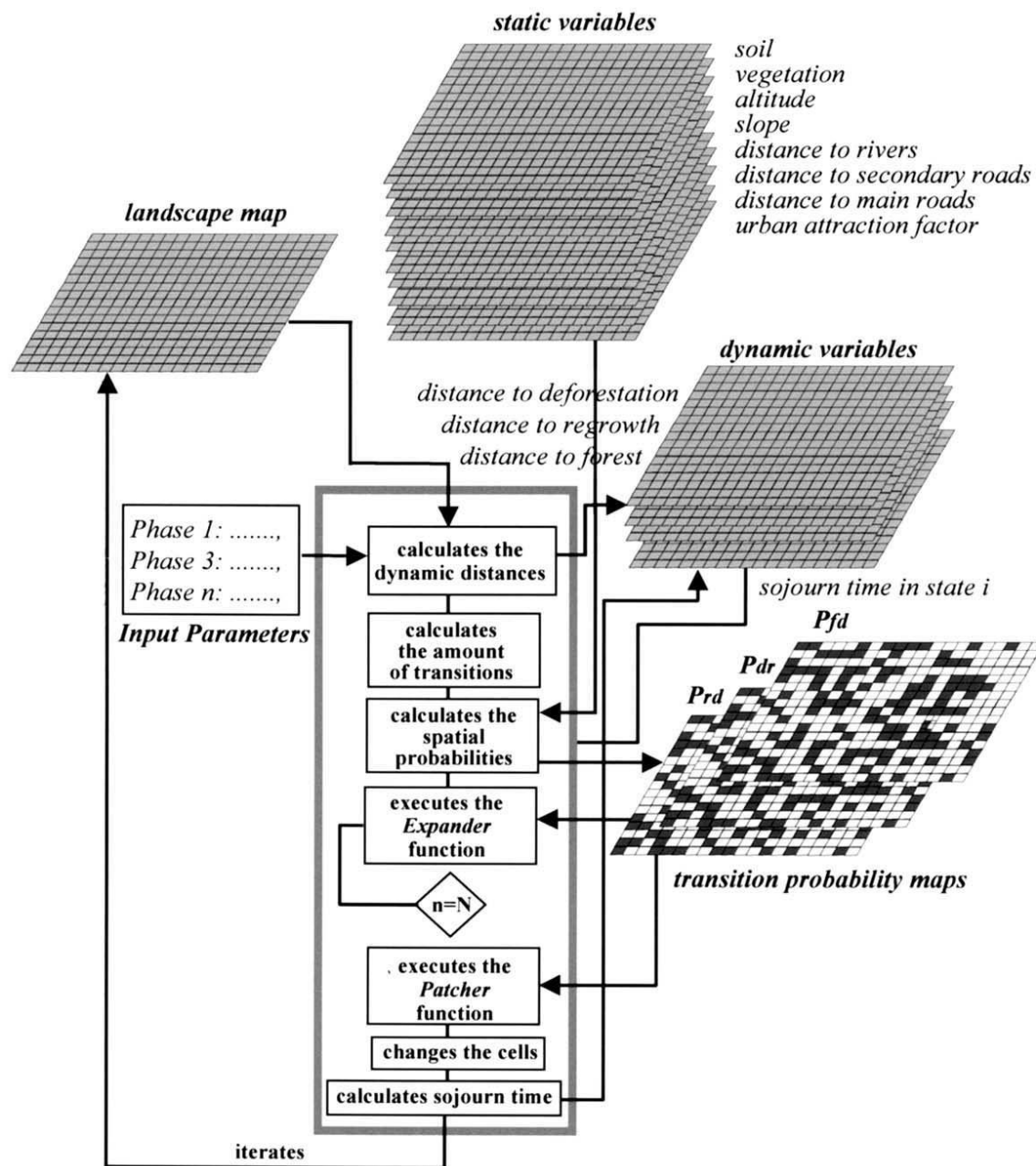


Figure 2.3 – Flowchart of DINAMICA operation.  
Source: SOARES-FILHO et al. (2002)

### 2.2.1. Neighborhoods definition in Dinamica EGO – A DINAMICA model implementation

In DINAMICA, the neighborhood influence in the transition probabilities is modelled by splitting the cell selection mechanism into two processes: (a) the *expander function*, dedicated only to the expansion or contraction of previous patches of a certain land-use and land-cover class; and (b) the *patcher function*, designed to generate or form new patches through a seedling mechanism (SOARES-FILHO et al., 2002). The combination of these two processes occurs through the equation below:

(1)

where  $Q_{ij}$  represents the total amount of transitions of type  $ij$  per simulation step;  $r$  and  $s$  are, respectively, the percentage of transitions executed by each function, being  $r + s = 1$ .

To compute the *expander function* the mechanisms provided by the framework considers as cell candidates to be a neighbor only the adjacent cells in a  $[n \times n]$  connected window, where the modeler defines the  $n$ 's value.

### 2.3. Geographic Automata System (GAS)

The *Geographic Automata System* approach (BENENSON; TORRENS, 2004; TORRENS; BENENSON, 2005) combines the concepts of CA based environments and Multi-Agent Systems (MAS), extending it to enable the explicit consideration of space and spatial behavior. It is an attempt in formalizing an object-based view of city structure and functioning within a simulation perspective in urban planning. The GAS concept treats urban infrastructure and social objects as *spatially located automata* named *Geographic Automata* (GA) (BENENSON; TORRENS, 2004). The notions incorporated into the GA are defined in Benenson and Kharbash (2005) as below:

1. An abstract automaton  $\mathbf{A}$  is characterized by a (vector) state  $\mathbf{S}$ , which changes in time according to state transition rules  $\mathbf{T}$ , depending on current input  $\mathbf{I}$ .
2. Cellular Automata theory considers  $\mathbf{A}$ 's neighborhood  $\mathbf{N}(\mathbf{A})$  and assumes that input  $\mathbf{I}$  is defined by an automata belonging to the  $\mathbf{N}(\mathbf{A})$ .

3. Agent **A** of a MAS can relocate in space, that is, its representation should be capable of managing location and neighborhood change over time.

The minimal set of transition rules **T** for a *Geographic Automaton G* should thus specify changes in:

1. Non-spatial attributes of **G**'s state;
2. Location of **G**;
3. Relationships among **G** and other *Geographic Automata*.

Geographic objects and their relationships are then specified as *Geographic Automata*. In GAS, the space is represented as collections of *Geographic Automata*. It also defines an independent set of geo-referencing rules for situating a GA in space. There are two types of GA: *Fixed Geographic Automata* and *Non-fixed Geographic Automata*. *Fixed GA* represents objects that not change their location over time. It may be subject to any transition rules, except rules of motion. *Non-fixed GA* represent objects that change their location over time, and the full range of transition rules can be applied over them. A GA can be geo-referenced directly or indirectly. Fixed ones are geo-referenced by recording their position coordinates, which does not change over time. Non-fixed GA are geo-referenced indirectly by pointing to other *Geographic Automata*. Figure 2.4 illustrates the two ways of geo-referencing GA in the GAS model. The structure of the urban space is defined by *spatial relationships* between these sets of GA.

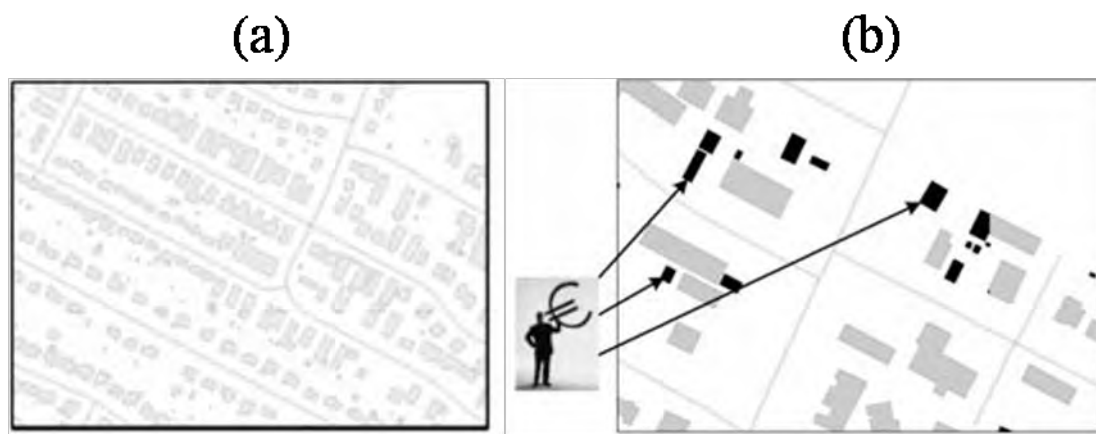


Figure 2.4 – Geo-referencing scheme in GAS (a) Direct – Buildings are represented by means of foundation contours, and roads by means of road boundaries; (b) Indirect – Locating a landowner by pointing to his/her properties. Source: Adapted from TORRENS and BENENSON (2005)

### 2.3.1. Neighborhoods Definition in OBEUS – A GAS model implementation

*Object-Based Environment for Urban Simulation* - OBEUS is a system that operationalizes the GAS concept (BENENSON; KHARBASH, 2005). Conceptually, the neighborhoods in a GAS modeling approach can be defined based on the types of GA. For *Fixed GA*, the neighborhood can be defined by a set of possible *spatial relationships* among *Fixed Objects*. For *Non-fixed GA*, the neighborhood relations are dynamic in space and time. When the geo-referencing rules are based on indirect location, two indirectly located objects can be considered neighbors when the object they point to are neighbors, as shown in Figure 2.5. In this case, neighborhood cannot be obtained directly, but making use of transitivity as a property of the relations. OBEUS takes these GAS concepts and selects to follow the classical Entity-Relationship Data Model (ERM) (HOWE, 1983) and the Object-Oriented (OO) programming paradigm (BOOCH, 1994) as the main guidelines for its computational implementation of a GAS-based Modeling platform. Therefore, it explicitly considers relationships between entities. Such as in the Relational DBMS theory, *relationship objects* and their properties are stored in *tables* just as the *objects* representing geographic entities. The neighborhood structure, in this case, is represented as a set of *relationship objects* linked to specific kinds of GA structures. The idea is to take advantage of the relational-based computational engine by using a *relationship class* and a *table* presentation. With that strategy, OBEUS claims it makes simpler to do on the fly evaluations whether two GA's are related, that is to say they are neighbors.

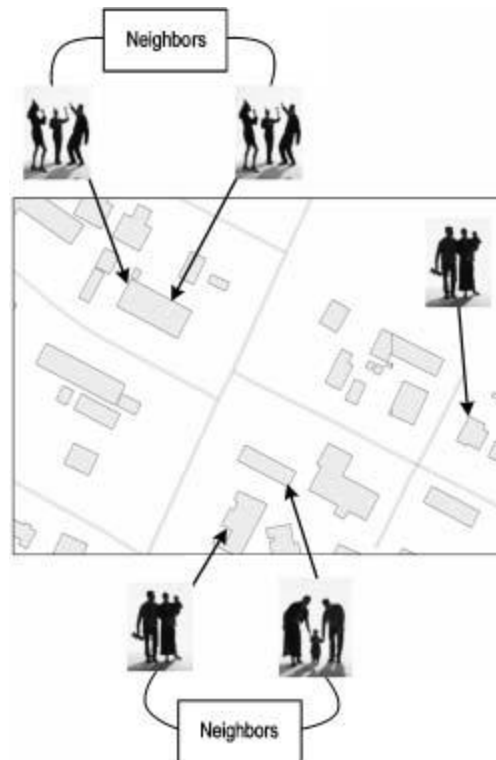


Figure 2.5 – Neighborhood relationships for indirectly GA. Two households are neighbors if they are located in the same property or in neighboring properties.

Source: TORRENS and BENENSON (2005)

However, as the conceptual GAS model is a dynamic system, the properties of GA, as well as their set of *relationships*, change over time. In OBEUS, the GAS computational implementation, essential limitations are imposed to the semantics of the *relationships*, in order to avoid inconsistencies:

1. First, it is assumed that relationships between *fixed GA* are also *fixed*, i. e., once established, they do not change;
2. Second, it is not permitted direct relationships between *non-fixed GA*. Thus, *non-fixed GA* can only be related to *fixed GA*. *Non-fixed GA* maintain *relationships* in a transitive way. A *non-fixed GA* is related to another *non-fixed GA* only, and if only, they are both related to a specific *fixed GA*. However, direct relationships between *non-fixed objects* are undoubtedly important in the real world.

#### 2.4. Nested-CA model

The Nested-CA model was introduced by Carneiro (2006). Essentially, it is a CA extension oriented to the development of a computational approach for modeling and

simulation, where an ecological concept of *scale* plays a central role. It considers a *scale* as a set of three fully integrated dimensions: a spatial, temporal, and behavioral one. Handling each of them in isolation is not enough to produce the powerful computer representation models one needs for dealing with complex geographical and ecological phenomena. The Nested-CA approach (CARNEIRO, 2006) takes the ecological *scale* concept as the central semantic unit for its computational model. The CA is extended for fully integrated support of the Gibson's *scale* concept (GIBSON et al., 2000). In the Nested-CA, *scales* are taken as building-blocks, which can be hierarchically organized. This strategy allows for the development of spatially-explicit models in which higher hierarchical *scales* provide overall control to *scales* at the lower levels. Each *scale* has its spatial dimension represented by one single CA. However, this CA has been extended mainly in three ways: (1) first, it deals with less limited spatial representations, allowing free geometry for the cell-shape definition. This feature makes it possible to work with *cellular worlds* representations coupled with real-world geographical databases that can take points, lines, grids, polygonal shapes and even voxels structures into modeling (CARNEIRO et al., 2008); (2) second, it allows for a very flexible definition of the cell's neighborhood. Topological cells relationships are expressed in terms of *dynamic neighborhood graphs* (AGUIAR et al., 2000); (3) and third, putting the first two together, it can deal with N-dimensional spaces when and where this feature is needed.

Last, but not least important, *Event Schedulers* for dealing with discrete events over a continuous time basis are basic components for the *time scale* dimension, and *Infinite-State Machines* (HENZINGER, 1996) are the building-blocks for the *behavioral scale* dimension. *Event Schedulers* and *State-Machines* are embedded into the Nested-CA macro structure, which represents the whole *scale* concept. That is actually what makes the conceptual *scale*-based organization a *Nested* approach: it is nesting a set of extended CA-structures and, it is computationally taking care of controlling this built nest fully integrated and making it transparent to the model builder. Figure 2.6 shows schematic representations of a Nested-CA model arrangement, based on its fundamental *scale* units. A more detailed description can be found in (CARNEIRO, 2006).

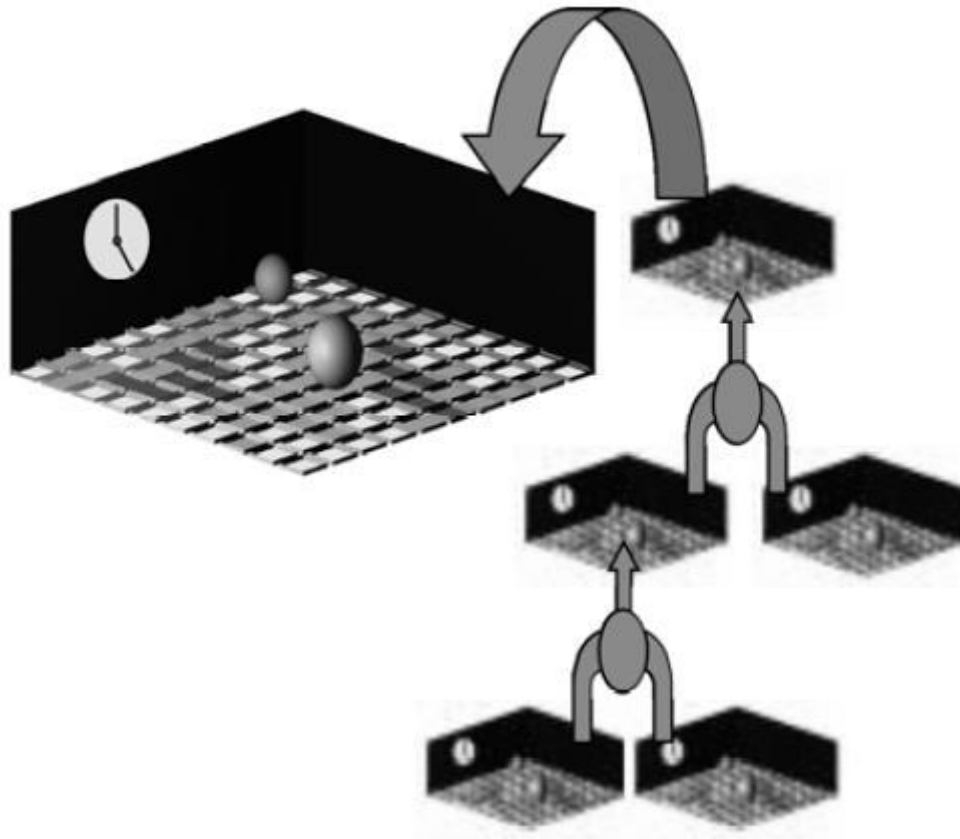


Figure 2.6 – Nested-CA structure.  
Source: CARNEIRO (2006).

#### 2.4.1. Neighborhood Structures in the Nested-CA model

The Nested-CA model defines neighborhood for cells that belong to its *scales* using the *Generalized Proximity Matrices* (GPM) concept (AGUIAR et al., 2000). The GPM is an extension of the of the *spatial weights matrix* originally proposed in the context of statistical spatial data analysis (BAILEY; GATTREL, 1995) to be used in the context of spatial dynamic modeling and simulation. The main idea is to accommodate the notion of *relative space* when defining a neighborhood structure and extend that by using graph-based structures (TAKEYAMA; COUCLELIS, 1997; O’SULLIVAN, 2001a, 2001b). In Nested-CA, the GPM is the basis for dealing with a neighborhood structures definition. Isotropic and non-isotropic neighborhood structures (AGUIAR et al., 2000) can be defined by using the GPM. Figure 2.7 illustrates the use of this concept to define two neighborhoods considering a transportation network and two [3x3] traditional cell-neighborhood structures.



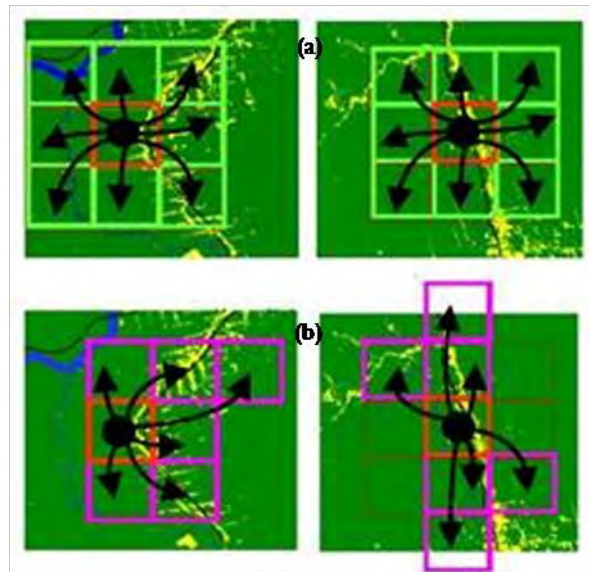


Figure 2.7 – Neighborhoods defined using the GPM concept. (a) Moore neighborhoods. (b) Two non-isotropic neighborhoods defined through a transportation network.

Source: adapted from ANDRADE-NETO et al. (2008).

However, despite all the flexibility to define the neighborhood structures, once they are defined, they cannot be reconfigured during the model life cycle, in particular they cannot be changed automatically by situations that can pop up at running time, triggered by the internal and/or external dynamics of the executing model. That is to say, following the example of roads shown in Figure 2.7, if a new road is created by an event during the model running time, this change will not be reflected in future decisions on the next cycle of the model, because the cells neighborhood structure will not change due to this new road included. It needs improvement.

## 2.5. VecGCA model

VecGCA model is a vector-based geographic CA model presented by Moreno et al. (2008), where the space is represented as a collection of geo-referenced interconnected irregular geographic objects. Each object is in a specific state and can have its proper transition function, according to the area of the neighbor and the influence exerted by it. During the execution of the model, these objects change its shape and size, when part of its area changes its state.

The transition function is defined to quantify the area of each object that changes its state and is evaluated for each neighbor of the object. Such area is related to the area of the neighbor and its influence on the specific object, which is constant over the whole

surface of it. This function is equals to 0 when the influence of the neighbor is smaller than a threshold value ( $\lambda$ ), which represents the resistance of the object to change its state to the state of the neighbor. The total area of the object is the upper limit, when the whole object changes its state.

The geometric transformation reduces the area of the object by removing a quantity from the region nearest to the corresponding neighbor. It is executed  $n$  times in each time step, once for each neighbor, for which the transition function is greater than 0. It is executed from the neighbor with the highest influence to that with the lowest influence. To perform this transformation, the object is rasterized using a regular grid, which the resolution is defined by the user. The necessary amount of cells changes their state to satisfy the area calculated by the transition function.

Thus, the removed cells define a new object, which is then combined with the corresponding neighbor. Figure 2.8 illustrates this process.

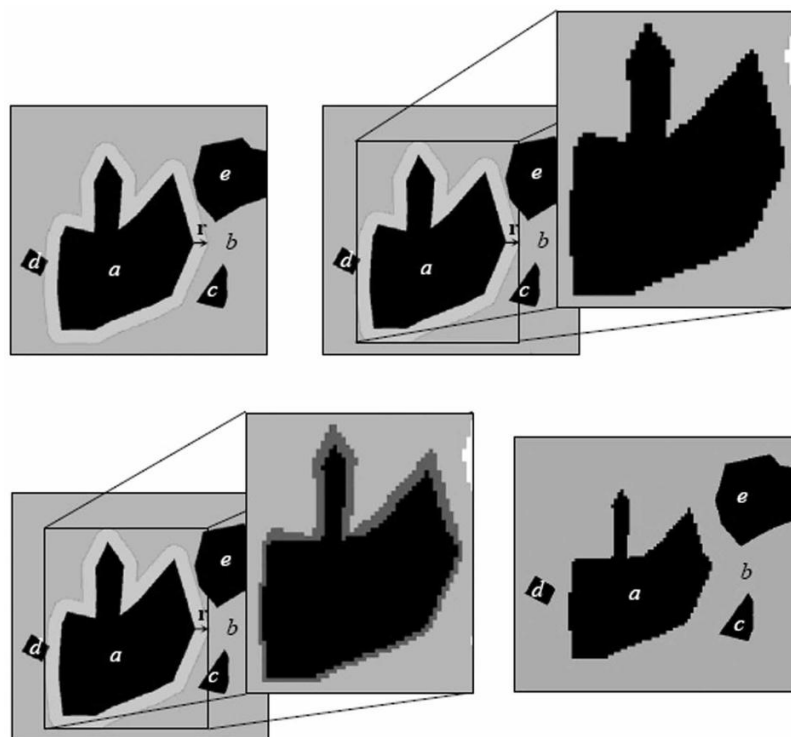


Figure 2.8 – Geometric transformation of an object in VecGCA.  
Source: MORENO et al. (2008).

In the original VecGCA, the neighborhood is defined as an external buffer  $d$  (region of influence) around each geographic object, and the objects (adjacent or not) that are

partially or totally within the region of influence, defined by  $d$ , are the neighbors of the central object.

### 2.5.1. Neighborhoods Definitions in VecGCA

In an attempt to reduce the sensitivity of the VecGCA model to the neighborhood configuration, Moreno et al. (2009) implemented dynamic neighborhoods in the VecGCA model. In this model, two objects are neighbors if they are adjacent, or separated by other objects, which states are favorable to the transition of states between them. There is no distance or fixed area that delineates it.

The neighborhood includes the whole space and is specific of each object. A binary matrix like that shown in Figure 2.9 (b) describes if a state  $X$  is favorable to the transition from the state  $Y$  to  $Z$ . The 1 value indicates that the state is favorable to the transition, and 0 indicates the opposite. This matrix indicates, for example, that commercial land is favorable to the transition from undeveloped to developed land, from undeveloped to commercial land, and from park to developed land. Figure 2.9 illustrates this structure. Thus, we can say, for example, that the neighbors of the object A are the objects B, C, D and E.

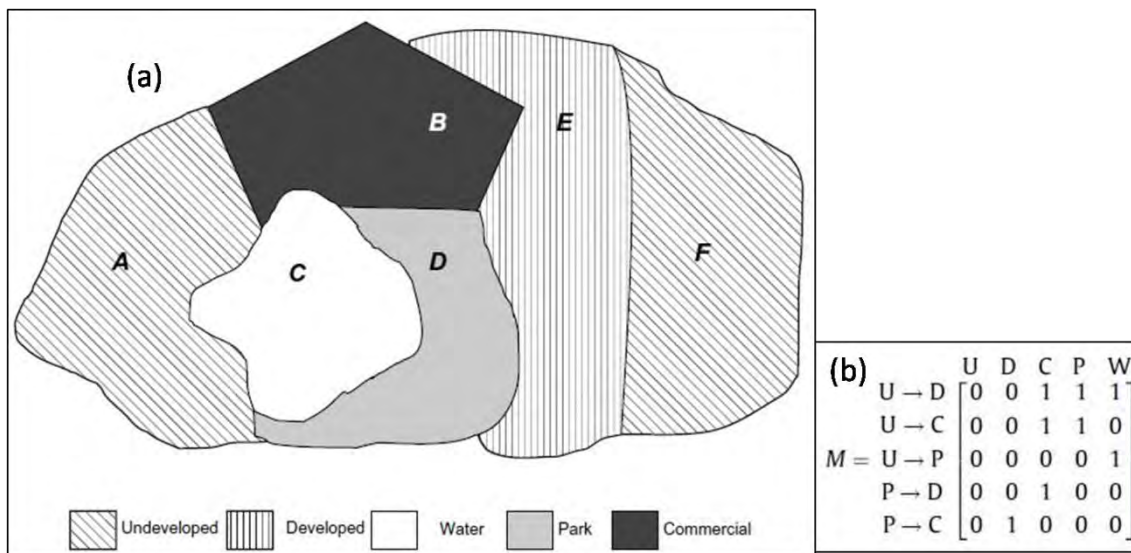


Figure 2.9 – (a) A VecGCA space and (b) the matrix that describes what states are favorable to the transition between what states.  
Source: Adapted from MORENO et al. (2009).

With this neighborhood definition, the influence value is variable on the surface of the central object. Such value increases when the neighbor is closer to the central object, with the maximum value ( $g_{max}$ ) in the object's border and decreasing inside the object.

If  $g_{max}$  is higher than the threshold value  $\lambda$ , then the geometric transformation is performed. The transition function calculates a buffer size around the central object, which is used in the geometric transformation procedure to take a portion of the central object, adding it to the corresponding neighbor.

The neighborhood structures in VecGCA can be reconfigured at run time, but they are entirely dependent on the previously transition table defined for the land-use and land-change model as a whole. The mechanism for changing a specific neighborhood structure is part of the running model as an adjustment of neighborhood relations, since objects in the model have made their transition from one state of land use to another. It does not produce a general mechanism for dealing with changes in neighborhood structures over space and time, and has its use strict to models based on transition tables.



### **3. A DYNAMIC NEIGHBORHOOD MODEL PROPOSAL: CONCEPT, FORMALIZATION AND IMPLEMENTATION**

This section presents a conceptual model for defining neighborhood structures that change over time. This conceptual model is an algebraic specification based on a graph-like structure, aimed to provide the basis for implementing a set of operators (functions). These operators allow dealing with a truly dynamic neighborhood structures definition for CA-based computational environments, designed for geographic modeling and simulation.

As a *proof-of-concept* and for evaluation of the proposed conceptual model, it was implemented in **TerraME** – *Terra Modelling Environment* ([www.terrame.org](http://www.terrame.org)), a computer platform that implements the Nested-CA model (CARNEIRO, 2006), presented in Section 2.4. This implementation was used to develop a deforestation model that incorporates dynamic neighborhoods structures. This deforestation model, described in Chapter 4, was based on the work of Amaral et al. (2006), which describe the deforestation patterns and the corresponding evolution of the transportation network in the Xingu-Iriri frontier, south of Pará State, in the Brazilian Amazon. It is important to notice that, in this work, the main focus of the deforestation model developed is not to reproduce exactly the real phenomenon, but present, in a real context, the possibilities of using the Dynamic Neighborhoods concepts to modeling a complex phenomenon.

#### **3.1. The Dynamic Neighborhoods (DN): A Conceptual Model**

##### **3.1.1. Defining the GPM-*Generalized Proximity Matrices***

Based on the idea that spatial relations in geographic space are more complex than simply the Euclidean space metrics, currently most used and available in GIS systems, Aguiar et al. (2003) proposed the concept of *Generalized Proximity Matrices (GPM)*. It is an extension of the of the *spatial weights matrices*, originally proposed in the context of statistical spatial data analysis (BAILEY; GATTREL, 1995), to be used in the context of spatial dynamic modeling and simulation. The main idea is to accommodate the notion of a *relative space* when defining a neighborhood structure, and extending that by using graph-based structures (TAKEYAMA; COUCLELIS, 1997; O’SULLIVAN, 2001a, 2001b). It combines the notion of space as a set of *absolute locations* in a Cartesian coordinate system, named *absolute space*, with the

notion of space as a set of *spatial relations*, which are dependent on topological connections and fluxes along physical or virtual networks, named *relative space*.

The GPM allows the extension of spatial analysis formalisms and techniques to incorporate relations on *relative space*, providing a new way for exploring complex spatial patterns and non-local relationships in CA-based dynamic models. Recent developments have extended the GPM approach, positioning it as a generic way for expressing spatial relations between geographic objects such as cells and agents (MOREIRA et al., 2008; 2009).

Formally, a GPM can be defined as follows:

Being a set  $O$  of spatial objects whose geometrical representations are defined over a connected subset  $S \subset \mathbb{R}^2$ . Given two objects  $o_i$  and  $o_j$  belonging to  $O$ , the proximity relation between them is denoted  $w_{ij}$ . The GPM is defined as a set  $W$  of triplets  $(o_i, o_j, w_{ij})$ , where each pair of elements  $(o_i, o_j)$  is associated to a combined proximity measure  $w_{ij}$ . Additional information about the network relations between the objects in  $O$  are given by a graph  $G$  over subset  $S$ .

The computation of each element  $w_{ij}$  of the GPM requires two proximity measures, defined by the functions *proxabs* and *proxrel*, which are associated to absolute space and relative space, respectively. Basically, each  $w_{ij}$  is calculated as following:

(3.1)

### 3.1.2. An Algebraic Definition for Dynamic Neighborhoods Structures

Consider the following sets:

- $C$ : set of cell-objects, in which each cell  $c_i \in C$  is a simplified representation of an object  $o_i \in O$ ;
- $CSS$ : set of cellular spaces, where each cellular space  $CS_i \in CSS$  is a subset of  $C$  containing cells working in the same scale;
- $G$ : set of directed graph-like structures representing the relations among elements from  $C$ . Each graph  $g_i \in G$ , which represents the neighborhood of the cell  $c_i$ , is composed by a set  $V_i = \{c_j, c_k, \dots, c_m\}$  of vertices and a set  $E_i = \{(c_i, c_j), (c_i, c_k), \dots, (c_i, c_m)\}$  of edges.

- $W$ : GPM containing the weights of the relations among cells. Each element  $w_{ij} \in W$  is the weight of the relation between the cells  $c_i$  and  $c_j$ ;
- $M$ : set of dynamic models;
- $P$ : set of spatial processes, where each process  $p_i \in P$  represents a geographic phenomenon being modeled by a corresponding model  $m_i \in M$ ;

In order to define the following concepts, the function  $f$  from the equation 3.1 above will be taken as the function  $f_w \in FW$ , where  $FW$  is the family of functions for computing  $w_{ij}$ . From the  $FW$  family, another family of functions  $F$  is defined, where a specific function  $f_{NL} \in F$  for each pair of cells  $(c_i, c_j)$  establishes a *neighborhood law* for an entire  $CS$  set, or among two or more  $CS$  sets.

Having defined these sets and functions above, we will introduce a typology of modeling situations in which a neighborhood structure runtime reconfiguration is a requirement, from a modeler's perspective, to produce more adherence between the modeler's knowledge of the phenomena dynamics and his/her possibilities of code that into the executable model.

1. ***Endogenous change of the neighborhood structure:*** Consider we have a spatial process  $p_i \in P$  being modeled by a dynamic model  $m_i \in M$ . During the  $m_i$  life, the modeling structures change, creating new objects or changing existing ones. These changes are made by a modeling structure from  $m_i$ . Once it causes changes in the neighborhood of a cell  $c_i$ , the graph  $g_i$  needs reconfigurations, and the weights  $w_{ij}$  corresponding to each  $g_i$  vertex needs to change, in order to ensure that the neighborhood follows the model evolution. It is called *endogenous* because the forces causing changes came from inside  $m_i$ , i. e., from inside the spatial process  $p_i$  being modeled. Figure 3.1 shows a scheme of this.



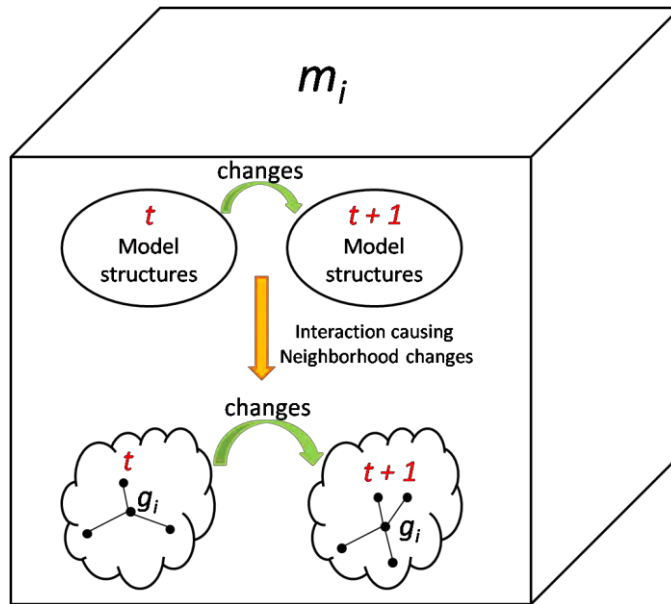


Figure 3.1 – Scheme of the endogenous change of the neighborhood structure.

2. **Exogenous change of the neighborhood structure:** Consider we have  $n$  spatial processes  $\{p_1, p_2, \dots, p_n\} \in P$  being modeled by the models  $\{m_1, m_2, \dots, m_n\} \in M$ , where each  $m_i$  models a corresponding process  $p_i$ . The models are running in parallel and interacting among them. At a certain moment, a change that occurs in a model  $m_j$  may cause a change in the dynamic behavior of a model  $m_i$ . This change may be in the neighborhood of a cell  $c_i$  of the model  $m_i$ , and the graph  $g_i$ , which represents its neighborhood, needs reconfigurations, even as the weights  $w_{ij}$  corresponding to each  $g_i$ 's vertex. It is called *exogenous* because the forces causing changes came from outside  $m_i$ , i. e., from outside the spatial process  $p_i$  being modeled by  $m_i$ . Figure 3.2 shows a scheme of this.

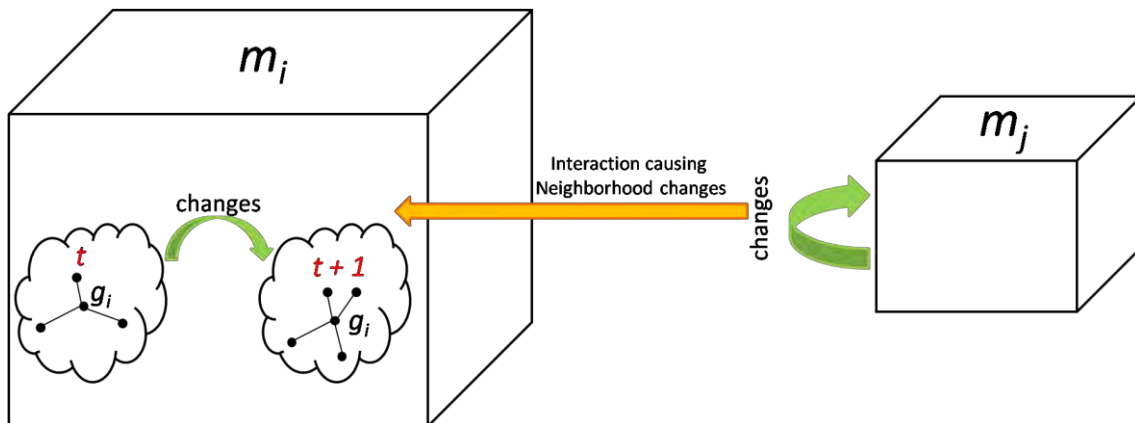


Figure 3.2 – Scheme of the exogenous change of the neighborhood structure.

3. **Hybrid change of the neighborhood structure:** In this case, the two previous ones occur in parallel. Considering  $n$  spatial processes  $\{p_1, p_2, \dots, p_n\} \in P$  being modeled by the models  $\{m_1, m_2, \dots, m_n\} \in M$ . At a certain moment, changes occur in some modeling structures of a model  $m_i$  and in some structures of another model  $m_j$ . The function  $f_{NL} \in F$  used to define the neighborhood of an object  $c_i$  (represented by the graph  $g_i \in G$ ) of  $m_i$  is defined considering both, the modeling structures of  $m_i$  and of  $m_j$ . When changes occur in the structures of any of both, it will reflect in the neighborhood of  $c_i$ , and  $g_i$  needs to reflect these changes, even as the weights  $w_{ij}$  corresponding to each  $g_i$ 's vertex. It is called *hybrid*, because the forces causing changes came from inside and from outside  $m_i$ , i. e., from inside and from outside the spatial process  $p_i$  being modeled by  $m_i$ . Figure 3.3 shows a scheme of this.

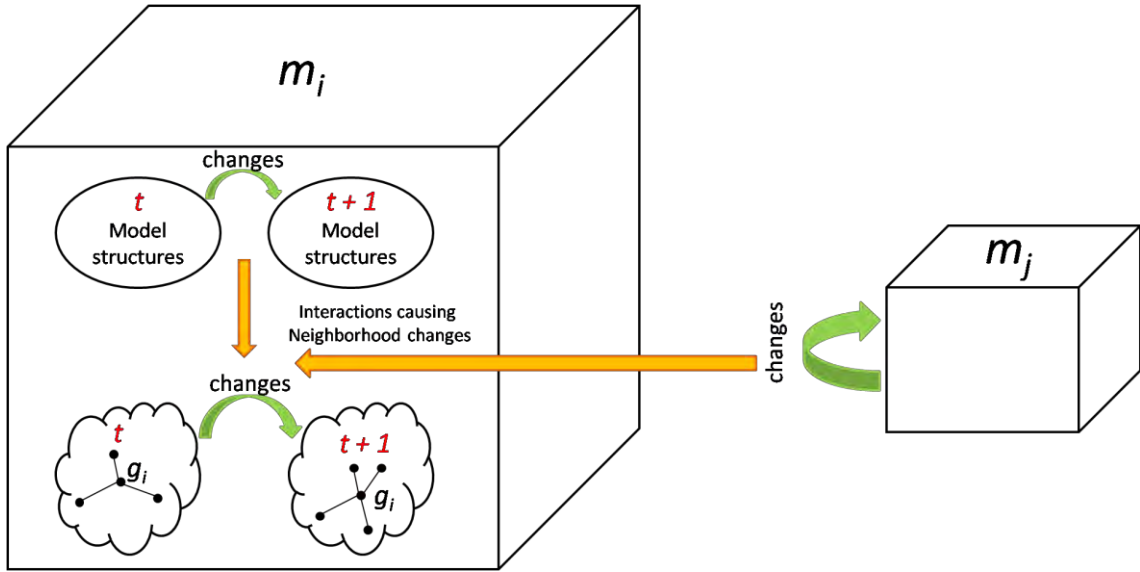


Figure 3.3 – Scheme of the hybrid change of the neighborhood structure.

For providing truly dynamic neighborhood structures reconfiguration at model runtime, first we need to define a set of basic functions and operators over those defined sets. Thus, it is important to bear in mind that they shall provide the means for dealing with the three (3) modeling situations described by the typology proposed here.

In order to do so, we need first to establish a set of atomic operators, which must operate at the cell,  $c_i \in C$ , level:

1. **Add:**  $(c_j, f_w(c_i, c_j), g_i, W) \rightarrow (g_i, W)$  denotes the operator that adds a cell  $c_j$  in the neighborhood of another cell  $c_i$ . Basically,  $c_j$  becomes a new node in the graph  $g_i = (V_i, E_i) \in G$  with a weight  $w_{ij}$ , calculated by the function  $f_w$ , which represents the strength of the relation. After adding  $c_j$  in  $V_i$  and the edge  $(c_i, c_j)$  in  $E_i$ , the weight  $w_{ij}$  is added in the GPM  $W$ . This operation is done as follow:

(3.2)

2. **Remove:**  $(c_j, g_i, W) \rightarrow (g_i, W)$  is an operator that removes the cell  $c_j$  from the neighborhood of another cell  $c_i$ . Basically, the node corresponding to  $c_j$  in the graph  $g_i \in G$  is removed, and the weight  $w_{ij}$  is removed from the GPM  $W$ . This operation is done as follow:

(3.3)

3. **SetWeight:**  $(c_i, f_w(c_i, c_j), g_i, W) \rightarrow (g_i, W)$  is the operator that sets the weight  $w_{ij}$  of the relation between the cells  $c_i$  and  $c_j$ . Basically, it changes the weight of the node that represents the cell  $c_j$  in the graph  $g_i \in G$  by changing the value of  $w_{ij}$  in the GPM  $W$ .

(3.4)

Besides the operators defined above, we need to establish some functions, which either act in a lower level (the cell,  $c_i \in C$ , level):

4. **GetWeight:**  $(c_j, g_i, W) \rightarrow w_{ij}$  is the function that given two cells  $c_i$  (the central cell in  $g_i$ ) and  $c_j$  (neighbor), returns the weight  $w_{ij}$  of the relation between them. Basically, it returns the element  $w_{ij} \in W$ .
5. **NeighborhoodLaw:**  $(c_i, c_j) \rightarrow \text{Boolean}$  is the function that defines the condition for considering two cells neighbors. Usually, it is defined by the modeler when the neighborhood is created, and does not change during the model life cycle. It receives two cells  $c_i$  and  $c_j$  and returns “true” if they

satisfy the condition and “false” otherwise. This condition could be defined, for example, in two ways:

- a. over the set  $A = \{(A_1, \preceq), (A_2, \preceq), \dots, (A_n, \preceq)\}$  of partially ordered domains of cells attributes, where  $a_i$  is the value of attribute  $(A_i, \preceq)$ , i. e.,  $a_i \in (A_i, \preceq)$ ;
- b. over spatial predicates. For example: given two cells  $c_i$  and  $c_j$ , they are neighbors if  $c_i$  “touch”  $c_j$ .

6. **Reconfigure:**  $(c_i, f_{NL}(c_i, c_j), f_W(c_i, c_j), CSS, g_i, W) \rightarrow (g_i, W)$  is the function that reconfigures the whole neighborhood graph  $g_i$  of cell  $c_i$ , based on instances of functions of the families  $F$  and  $FW$ , defined above. The traversal of the Cellular Spaces  $\{CS_1, CS_2, \dots, CS_n\} \in CSS$  is done by applying the function  $f_{NL} \in F$  to each pair of cells  $(c_i, c_j)$ , where  $c_i$  is the central cell of  $g_i$ . For each  $c_j$ , it executes:

(3.5)

To apply the **Remove** function to the neighbors of all cells of a *Cellular Space*, we need to traverse it by applying the function to each one of the cells.

Thus, the changes of the neighborhood structure can occur in two forms, which can even occur simultaneously:

- Changing the topology of  $g_i$ , i. e., changing the number of arcs and nodes;
- Keeping the topology of  $g_i$ , i. e., changing only some values of  $w_{ij}$ .

### 3.2. Dynamic Neighborhoods (DN): The Implementation Model

To evaluate the proposed conceptual model, an implementation of it was made in **TerraME** – *Terra Modelling Environment*, a computer platform that implements the Nested-CA model (CARNEIRO, 2006). To describe the implementation model, first the TerraME platform is described. After that, it is pointed the signatures for the functions described before and an overview of how they were inserted in **TerraME**.

### 3.2.1. The TerraME platform

**TerraME-Terra Modelling Environment-** is an open source software platform which implements the Nested-CA model and services for spatiotemporal data analysis and management, for building spatially explicit dynamic models (CARNEIRO, 2006). The **TerraME** Programming Language is an extension of the Lua programming language (IERUSALIMSKY et al., 1996), a powerful and expressive language specially designed for extending applications. The source code of a model in **TerraME** can be written in a text editor, and it is interpreted by the **TerraME** interpreter. Figure 3.4 shows a scheme of the **TerraME** Programming Environment.

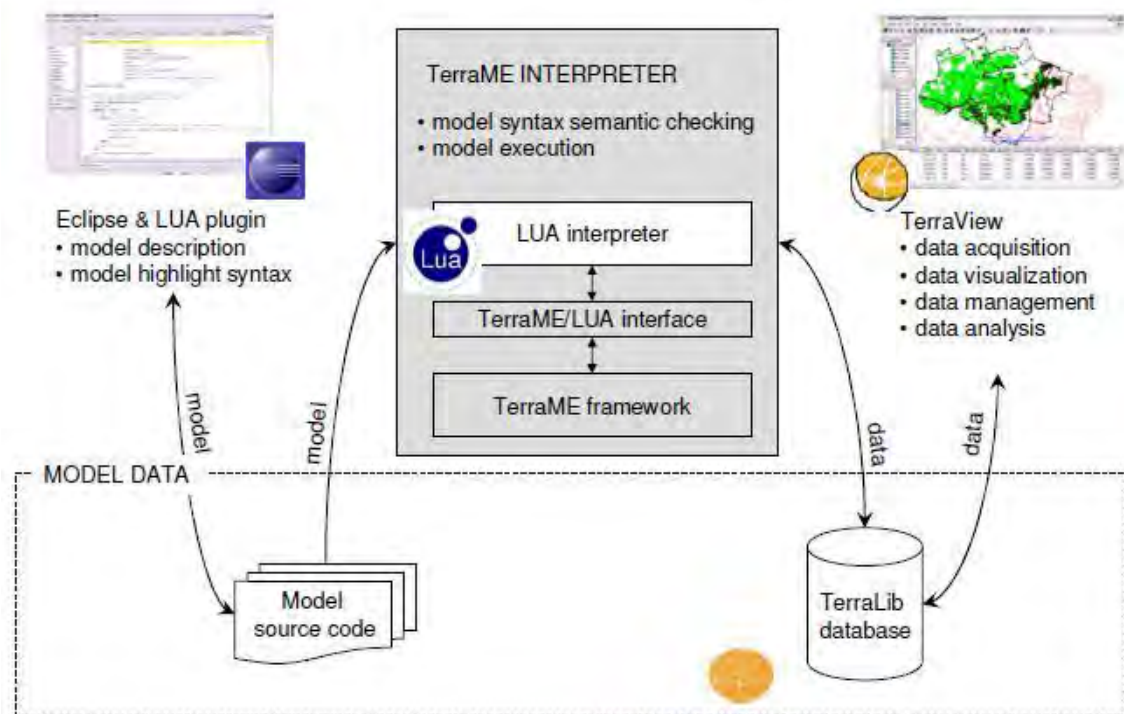


Figure 3.4 – The TerraME Programming Environment.  
Source: CARNEIRO (2006).

The inputs of the models are spatial data stored as GIS layers or in spatial data file formats. The outputs are *maps* that describe the spatial distribution of the variables involved with the phenomena being modeled. To support spatial data and spatial operations, **TerraME** is coupled with the **TerraLib** GIS library (CÂMARA et al., 2008), which provides services for model data input and output, data storage and spatial data management and operations. The input data and the outputs of the model can be visualized, manipulated, and analyzed in **TerraView**, a **TerraLib**-based GIS.

Like many other toolkits, **TerraME** was implemented in a *layered architecture*, shown in Figure 3.5. In this structure, the components of each layer implement their services calling the services of lower layers. It makes easier to reuse the layers and keeps the dependences locally.

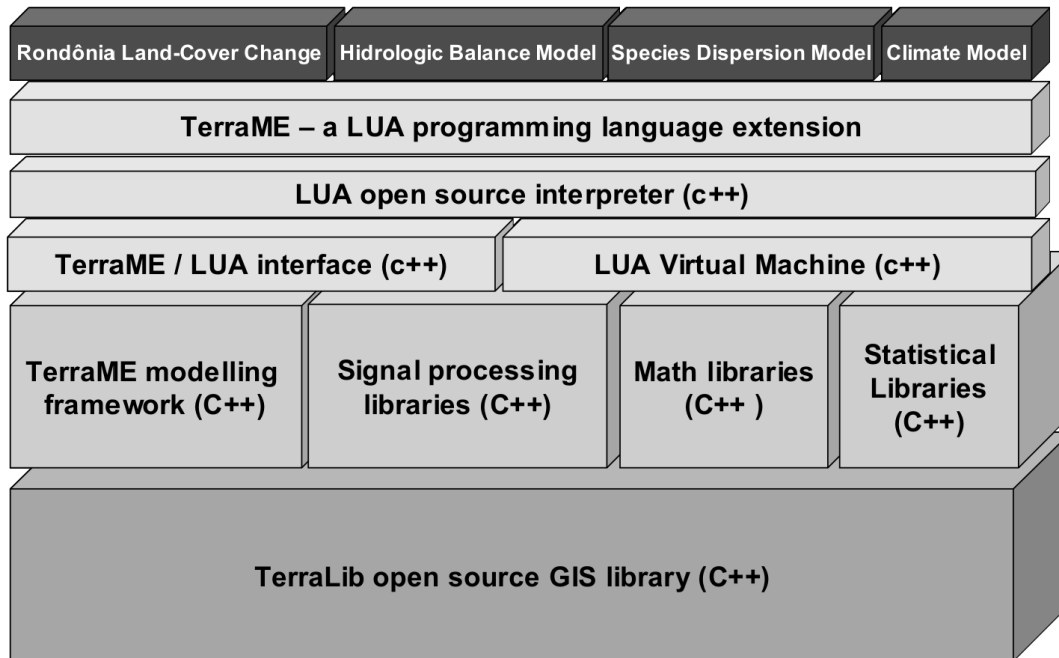


Figure 3.5 – TerraME Software Architecture.  
Source: CARNEIRO (2006).

Conceptually, the TerraME modelling framework is divided into three modules: *spatial*, *temporal* and *behavioral*. The temporal module implements the scheduler, i. e., all the functions that control the time of the model. The behavioral one implements all the functions that control the behavior of the components of the model, i. e. the state machines that control the behavior of each cell (local) and of the whole (global). And finally, the spatial module implements all the function that creates and manipulates the geographic space in the model, i. e., the cellular spaces and its functionalities, the cells and its functionalities, the trajectories and the neighborhoods. In this work, as we have done improvements in the neighborhoods structures, the implementation of this work was done in the spatial module.

### 3.2.2. The dynamic neighborhoods implementation

To incorporate the concept of dynamic neighborhoods in the **TerraME** modelling framework, we implemented the functions and structures described in Section 3.1.2 using Lua and C++ languages. The functions signatures and their operating modes are

described in this section. Most of them were implemented firstly in the **TerraME** kernel as functions written in C++, and afterwards, they were made available to the modelers as Lua functions, inserted in the TerraME programming language. The *spatial module* of TerraME is presented in the class diagram shown in Figure 3.6.

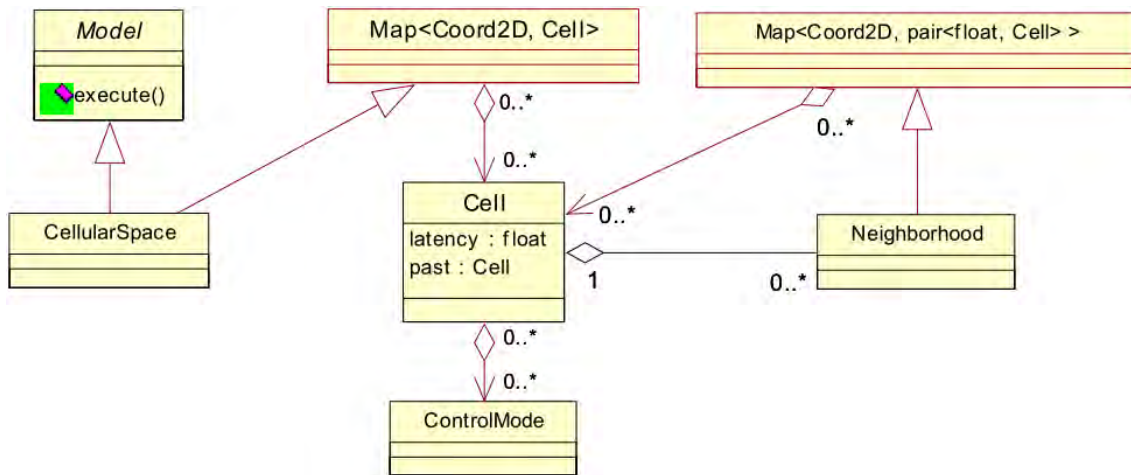


Figure 3.6 – Class diagram: Spatial module of TerraME.  
Source: CARNEIRO (2006).

Each *neighborhood object* is related to a *cell object*, and each *cell object* can have  $n$  *neighborhood objects* related to it. The *neighborhood object* stores and controls who are its neighbors, which are the *weights* for each relation, and what is the *neighborhood law* used to create it. The atomic functions previously described: *Add*, *Remove*, *SetWeight*, and *GetWeight*, which are used to manipulate the *neighborhood objects*, have the following signatures, and operates as described below:

1. ***Neighborhood.addNeighbor( cell, weight )***: this function receives a reference to a *cell object* and a *weight* (a real number) as parameters. It adds this cell with this weight to a *neighborhood object*, which is related to another cell (the central cell in a graph  $g_i \in G$ , described in Section 3.1).
2. ***Neighborhood.removeNeighbor( cell )***: this function receives as parameter a reference to a *cell object*, and removes it from a *neighborhood object*.
3. ***Neighborhood.setWeight( cell, weight )***: this function receives as parameters a reference to a *cell object* and a *weight*, and replaces the weight stored in the *neighborhood object* by this new one.

4. ***Neighborhood.getWeight( cell )***: this function receives as parameter a reference to a *cell object* and returns the weight stored in the *neighborhood object* for it.
5. ***Neighborhood.isNeighbor( cell )***: this function is an auxiliary function that receive as parameter a reference to a *cell object*, and verifies if it is in the current neighborhood, returning “true” if it is, and “false” otherwise.

The *neighborhood law* and the  $f_w$  (here called *fWeight*) functions, used in the *reconfigure* function, were not implemented, because they are created by the modeler, when constructing the model. But, these functions have a predefined signature, which need to be defined as follows:

6. ***Boolean neighborhoodLaw( cell\_1, cell\_2 )***: This function receives two cells as parameters. It needs to define a condition, by which these two cells will be considered neighbors or not. If these cells satisfy this condition, the function returns “true”, otherwise it returns “false”.
7. ***Double fWeight( cell\_1, cell\_2 )***: This function receives two cells as parameters. It defines how the *weight* of the relation between them will be computed. It returns a real number, the *weight* of the relation.

The *reconfigure function* has the following signature, and operates as described below:

8. ***Neighborhood.reconfigure( cs, neighborhoodLaw, fWeight )***: This function receives three parameters:
  - A cellular space (*cs*), where the cell, which the neighborhood is being reconfigured, has neighbors;
  - The *neighborhood law* function that defines the condition to consider two cells as neighbors;
  - The weighting function ( $f_w$ ) that calculates the weight of the relation between two cells.

It transverses all *Cellular Spaces* related to the current neighborhood being reconfigured, applying the *neighborhoodLaw()* function for each cell. In this way, the *reconfigure( )* function verifies what cells satisfy the condition



defined by the *neighborhood law*. If the current cell satisfies this condition, it does:

- a. First, applies the *isNeighbor()* function, to verify whether it is a neighbor in the current neighborhood or not.
  - If the *isNeighbor()* function returns “false”, it just adds the current cell in the structure with the *weight* computed by the *fWeight()* function, using the *add()* function.
  - If it returns “true”, it just adjusts the weight of the relation, changing the current weight by that calculated by *fWeight()*, using the *setWeight()* function.

If the current cell does not satisfy the condition defined by the *neighborhoodLaw()* function, it does:

- a. It also applies the *isNeighbor()* function;
  - And, if the *isNeighbor()* function returns “true”, it just removes the current cell from the neighborhood, using the function *remove()*.
  - If it returns “false”, it does not do anything.

Figure 3.7 presents the pseudocode of the *reconfigure()* function, where *cs* is a cellular space, *cell* is the “central” cell of the neighborhood, i. e., the cell for which the neighborhood will be reconfigured, and *cell<sub>i</sub>* is the *i*-th cell during the traversal of the *Cellular Spaces*.

```

cell.Neighborhood.reconfigure( cs, neighborhoodLaw, fWeight)
  For Each Cell from cs
    IF <neighborhoodLaw(cell, celli) = "true"> THEN
      IF <isNeighbor(celli) = "false"> THEN
        add( celli, fWeight(cell, celli) )
      ELSE
        setWeight( celli, fWeight( cell, celli) )
      END
    ELSE IF <neighborhoodLaw(cell, celli) = "false"> THEN
      IF <isNeighbor(celli) = "true"> THEN
        remove(celli)
      END
    END
  END
END

```

Figure 3.7 – Pseudocode of the *reconfigure()* function, where: *cs* is a *Cellular Space* and *cell<sub>i</sub>* is the *i-th* cell during traversal of it.

In addition to these functions, other auxiliary functions are needed, which can be used in the changes caused by the interaction among the models, in the *exogenous* and *hybrid* modes of operation, and to enable future analyses of the neighborhood structures and their evolution during the model execution. These functions aim to promote the persistence of the neighborhoods, which can be done in two ways: in a file system, or in a database scheme. One of these functions is:

1. ***CellularSpace.loadNeighborhoodFile(fileName, neighID)***: loads a full neighborhood structure from a chosen file. It receives as parameters the name of the file to be loaded and the unique identifier of the neighborhood. This function supports three types of files: *Binary contiguity relationships* file (\*.gal), *Generalized Weights Format* (ANSELIN, 2003) file (\*.gwt) and the *Generalized Proximity Matrices* file (\*.gpm), which is an extension of the \*.gal file for supporting the GPM structure.

The functions described until here were already implemented. Beside it, other functions are needed to make the neighborhoods' persistence more consistent. The functions described below were not implemented yet. These functions were designed and its requirements and structures are described here:

2. ***CellularSpace.saveNeighborhoodFile(time, filename, neighID)***: This function should saves the full neighborhood structures of an entire

*cellular space* in a chosen file during the simulation process. Its probable parameters are: the current time of the model (*time*), the name of the file to be created and the unique identifier of the neighborhood to be saved. It should also supports the \*.gal, \*.gwt and \*.gpm files.

3. ***CellularSpace.saveNeighborhood(time, neighID)***: This function saves the full neighborhood structures of an entire *cellular space* in a TerraLib database during the simulation process. Its probable parameters are: the current time of the model and the unique identifier of the neighborhood to be saved. Figure 3.8 shows an entity-relationship model of the proposed structure to save neighborhoods in a TerraLib database.

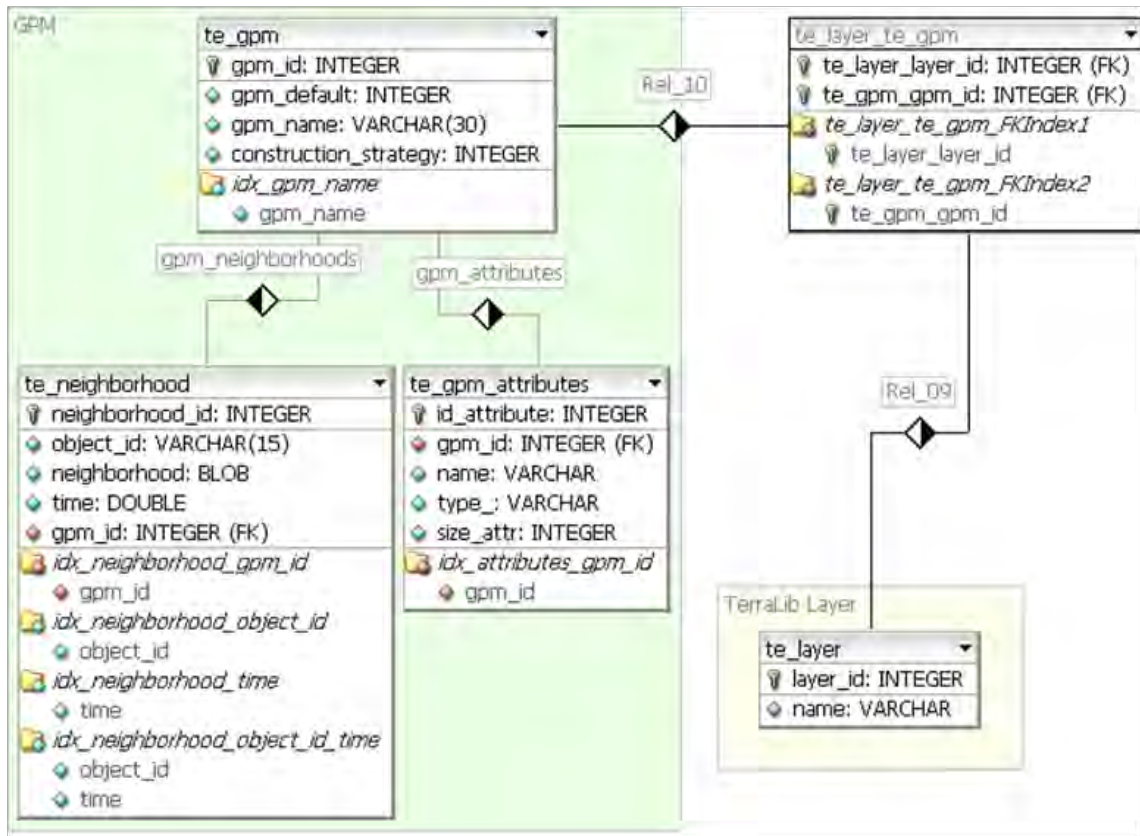


Figure 3.8 – Entity-relationship model of the proposed structure to save neighborhoods in a TerraLib database.

4. ***CellularSpace.loadNeighborhood(time, neighID)***: loads the full neighborhood structures of an entire *cellular space* from a TerraLib database, following the structure shown in Figure 3.8. Its probable parameters are: the current time of the model and the unique identifier of the neighborhood to be loaded.

5. ***Cell.saveNeighborhoodChanges(time, neighID)***: saves just part of the neighborhood structures of an entire *cellular space* in a TerraLib database. It is important because, in some cases, we have just a few changes in the neighborhoods between two iterations, and it is better to store just the parts that underwent changes than to store the full structure. Saving the full structure in these cases, would lead to redundancy in the stored data. Its probable parameters are: the current time of the model and the unique identifier of the neighborhood to be saved.
6. ***CellularSpace.loadNeighborhoodChanges(time, neighID)***: loads just part of the neighborhood structures of an entire *cellular space* from a TerraLib database. Its probable parameters are: the current time of the model and the unique identifier of the neighborhood to be loaded.

Rodrigues, (2008) has implemented in the TerraME framework, a tool for graphical visualization of dynamic models, called TerraME Observer. This implementation was made through the using of the Observer design pattern (GAMMA, 1995). Based on this implementation, we have implemented an extension of it for graphical visualizing the neighborhood graph of given *cell objects*. Figure 3.9 shows a screenshot of this visualization. The vertices and edges of the graph are represented by lines, which start in the central cell and ends in the neighbor one, and the weight of the relation is represented by the color of this line.

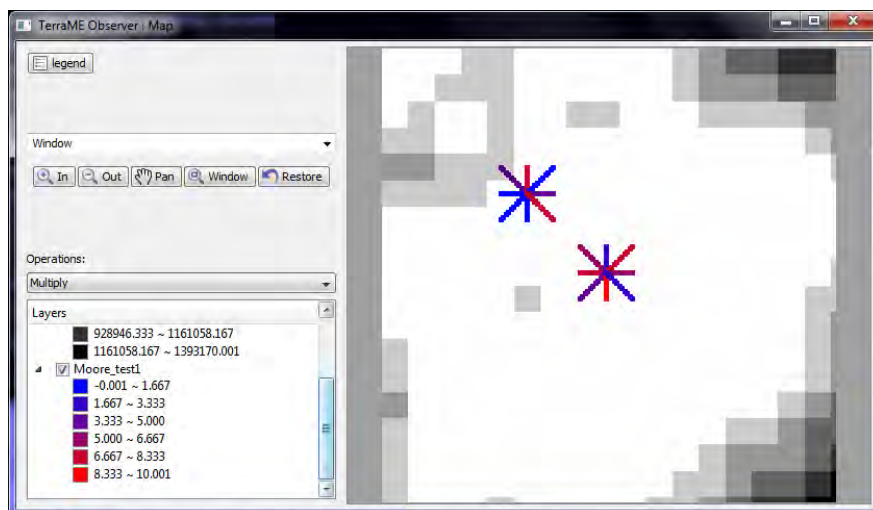


Figure 3.9 – Screen display of the neighborhood’s observer.

After defining all these functions above, we can define how would be their use in terms of implementing models that fit the typology previously proposed.

1. **Implementation of the endogenous change of the neighborhood structure:** in this case, just the functions using internal rules to manage the reconfiguration of the neighborhoods are used, i. e., the functions *addNeighbor()*, *removeNeighbor()*, *setWeight()* and *reconfigure()*. Using these functions, the modeler can define rules, through which the model will internally reconfigure the neighborhoods. Figure 3.10 shows a scheme of how it will operate.

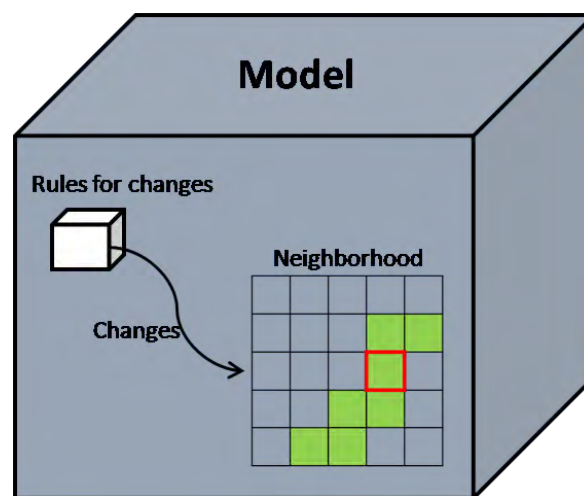


Figure 3.10 – Operational scheme of the endogenous change of the neighborhood structures.

2. **Implementation of the exogenous change of the neighborhood structure:** in this case, not only the functions to manipulating internal rules are used, but also the functions used to manage external data, i. e., data coming from another models or external sources. TerraME enables the execution of several models in parallel and interacting between them, through the *Environment* concept (CARNEIRO, 2006). Considering there are two models executing in parallel and, at a certain moment, changes occur inside Model 2, causing changes in the neighborhood structure of certain objects of Model 1. When it happens, Model 2 saves the neighborhood structure(s), or just the changes caused by it action, and shoots a trigger warning Model 1, which loads the new structures. Another case occurs when the models are not running in parallel, but the

operation is similar. When Model 2 is executed, it saves the structures for each time, and Model 1, when being executed, loads these structures for each time they are necessary. Figure 3.11 shows a scheme of how it operates.

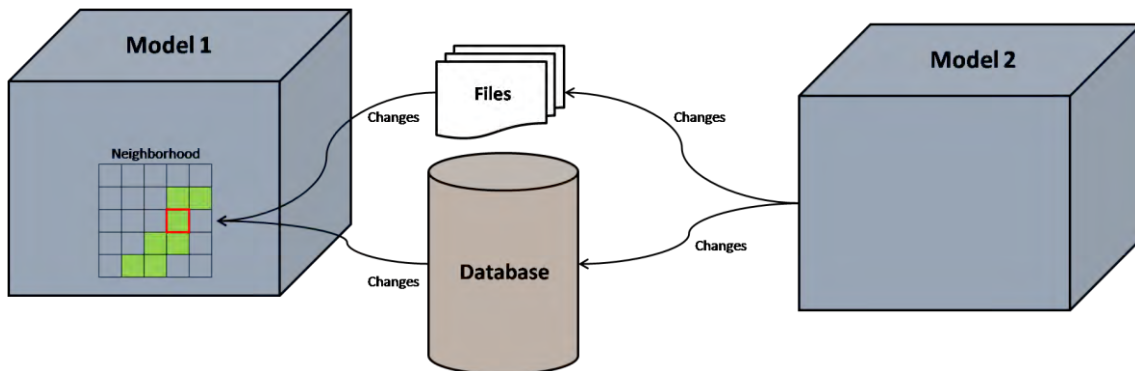


Figure 3.11 – Operational scheme of the exogenous change of the neighborhood structures.

3. *Implementation of the hybrid change of the neighborhood structures:*

In this case, we also use both, the functions for manipulating internal rules and the functions used to manage external data. However, here the two cases described above (endogenous and exogenous) will occur simultaneously over the same structure. Figure 3.12 illustrates the operational scheme of this case.

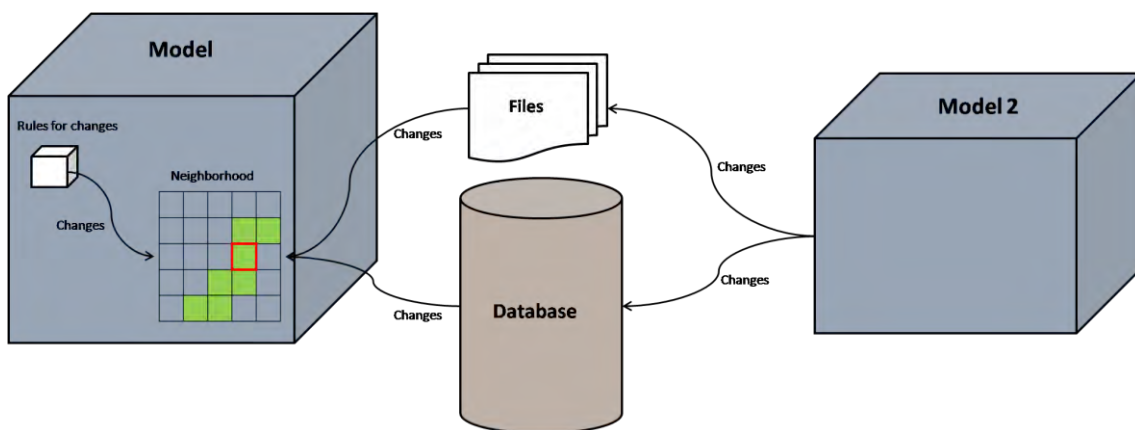


Figure 3.12 – Operational scheme of the hybrid change of the neighborhood structures.



#### 4. EXPLORING THE DYNAMIC NEIGHBORHOODS CONCEPTS IN A *PROOF-OF-CONCEPT* EXPERIMENT: MODELLING DEFORESTATION PATTERNS THROUGH CIRCULATION NETWORKS IN AN AMAZONIA FRONTIER SITE

In order to prove the concepts proposed in this work and test its implementation, we developed a deforestation model that needs the dynamic neighborhood concept. Based on Amaral et al. (2006) we simulate the evolving deforestation patterns in the Xingu-Iriri frontier, south of Pará State, in the Brazilian Amazon, over a period that goes from 2000 to 2009. There are two main reasons for choosing this case study to be our *proof-of-concept* experiment: (1) the fact that there is previous studies at INPE that are still going on (ALVES et al., 2010; AMARAL et al., 2009; ESCADA et al, 2005; AMARAL et al, 2006) describing the process of land cover change and its relation to the evolution of the transportation networks in that region; (2) the availability of an already built geographical database.

Basically the deforestation model developed aims to analyze the evolution of the deforestation patterns in the region, taking into account the *circulation networks*<sup>3</sup> as a major influence. These networks play a fundamental role in new frontiers, amplifying existing tendencies and intensifying certain processes linked to observed deforestation patterns (AMARAL et al., 2006). *Circulation networks* can accelerate the migratory process, as well as the local economic activities. Thus, they play an important role on local deforestation process.

Instead of concentrating the modeling process on the *roads-only-induced-deforestation* approach, the dynamics of this region allows for looking at the coupled dynamics, linking the observed deforestation patterns and the evolving *circulation networks* (CÂMARA et al., 2005).

##### 4.1. Study area and its Circulation Network Dynamics

The Xingu-Iriri frontier is a region between two important rivers, the Xingu River and the Iriri River. It is a territory mostly located in *São Félix do Xingu* and *Altamira* municipalities, also known as *Terra do Meio* (Figure 4.1 (a)). There are two main roads crossing the region, the Canopus road and the Farmers' road. Orthogonally to these

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<sup>3</sup> Circulation networks, for this study, are taken as informal multimodal transportation networks composed by roads, rivers and runways



main roads other secondary and auxiliary roads have been opened. In addition to that, there are a set of airstrips providing access entry points to the territory through small airplanes. All put together set up a multi-modal transportation network at a local scale named here as *circulation networks*. A schematic representation of it is shown in Figure 4.1 (b). It is with São Félix do Xingu that this territory establishes its strongest connectivity.

The Canopus road was built in the end of 80's. The Farmers' road was built in recent years (2002-2003). After its construction a segment of the Canopus road, near the Xingu River, was practically abandoned. Smallholders living nearby have undergone a decrease in their mobility and their access capabilities to reach for essential services and commerce.

Accordingly to Amaral et al (2006) the roads and rivers use patterns by the Terra do Meio population is seasonal. During the flood season, the get around is done mainly by the rivers. Some roads become blocked because of the large amount of holes, fall over bridges and roads segments entirely flooded. During the dry season, some of those roads start to be fixed and they come to be more used than the rivers.

Airstrips offer a peculiar access entry point to the region. Actually, they operate as connection nodes in a multi-modal transportation network. Keeping in mind that in this area, the *circulation networks* are based on precarious roads and rivers trails when available.

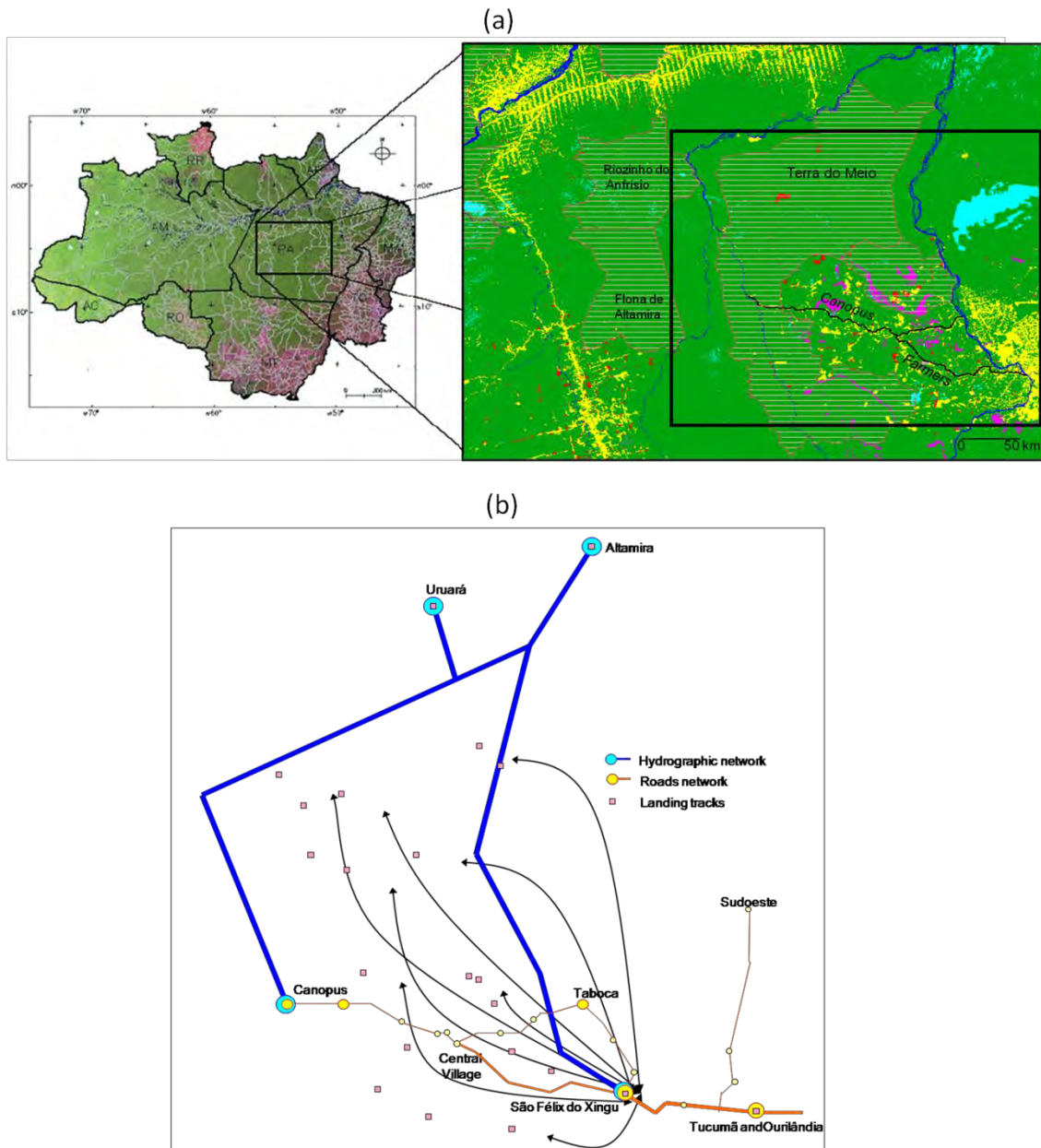


Figure 4.1 – (a) Legal Amazon, Terra do Meio and Xingu-Iriri Frontier (Rectangle area); (b) *Circulation networks* in the Xingu-Iriri frontier in 2006. Source: adapted from AMARAL et al. (2006).

#### 4.1.1. Model Rationality and Data Description

In order to monitor the annual deforestation produced by shallow cut in the Brazilian Amazon, INPE (National Institute for Space Research – Brazil) has measuring, since 1988, the annual deforestation rates trough the PRODES project. In addition to these rates, since 1997, INPE has been providing multi-temporal digital databases with the spatial distribution of the deforestation (INPE, 2011a; CÂMARA et al., 2006). The deforestation measured by PRODES consider only deforestation areas bigger than 6.25

hectares. Figure 4.2 presents a map showing the spatial distribution of the accumulated deforestation in 2000, used as input for the deforestation model developed.

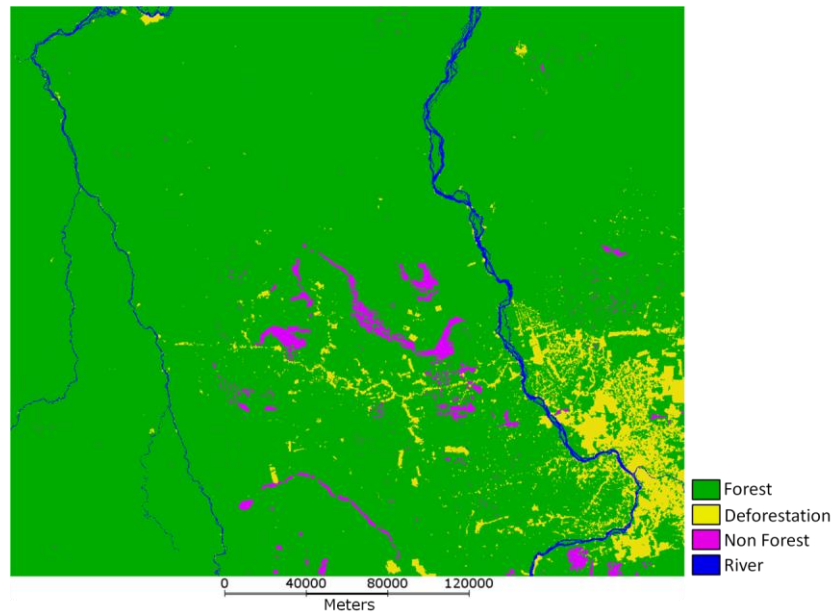


Figure 4.2 – Spatial distribution of the accumulated deforestation in 2000.  
Source: adapted from INPE (2011a).

Based on the deforestation map presented on Figure 4.2, a grid with squared cells of 4km x 4km (16 km<sup>2</sup>) was created and filled, generating two main attributes for each cell, “percentage of forest” and “percentage of deforestation”, even as two others, “percentage of non forest” and “percentage of river”. The filling of cells was made through the *Fill Cells* plugin, a TerraView extension developed to calculate attribute values of tables associated with cell type layers (AGUIAR et al., 2010). Figure 4.3 shows the spatial distribution of the attribute “percentage of forest” in the grid of cells, which was used as input data for the deforestation model.

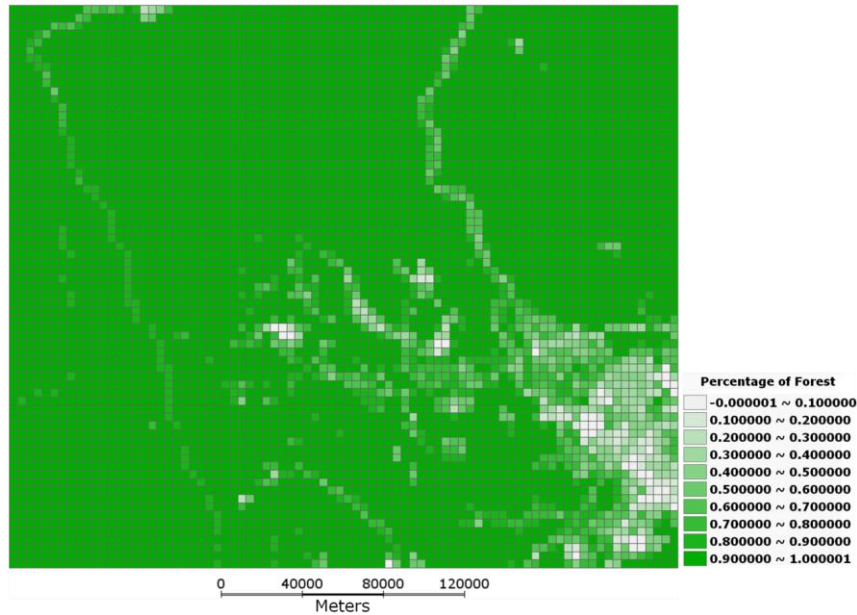


Figure 4.3 – Spatial distribution of the attribute “percentage of deforestation” in the grid of 4km x 4km cells

We consider that the roads network represents the main influence on the deforestation process being modeled. Figure 4.4 illustrates the roads network used. These data were collected in field works made by INPE researchers (AMARAL et al., 2006, 2007; ESCADA et al., 2005, 2007; PINHO et al., 2010; VIEIRA et al., 2004). The influence of the roads is not homogeneous in the whole network. For each road segment three parameters, which defines how stronger is its influence, were defined:

**Paving:** it determines if the road segment is paved or not. Paved segments exert a stronger influence than non-paved ones. Its values are: “Paved” and “Non-Paved”. It is important to notice that the unique paved road in the region is the “PA-279” (Figure 4.4), but once the main purpose of this deforestation model, in this work, is to demonstrate the use of the DN concepts, we consider that during the model execution some roads are paved, in order to increment the network dynamics. Thus, at the beginning of the model, only the “PA-279” is paved, and then at each year 5% of the roads segments are paved.

**Status:** It determines if the road is active or not. This attribute is used to represent the seasonality effects, deactivating the road segments located closest to rivers during the flood season. Its values are: “Active” and “Inactive”. We consider that when a road segment becomes inactive, it is impassable. Thus, inactive road segments do not exert any influence over its surroundings.

**Hierarchy:** Based on the importance of each road to the region, a hierarchy was defined. Its values are: “Primary” and “Secondary”. Thus, we consider that primary roads exert a stronger influence than secondary ones. However, during the simulation process, we increment the influence of some secondary roads, in order to reproduce the big farmers’ behavior, which in general are located in remotest areas.

**Year of creation:** It determines when the roads appear in the deforestation model, i. e., when they become to be considered by it.

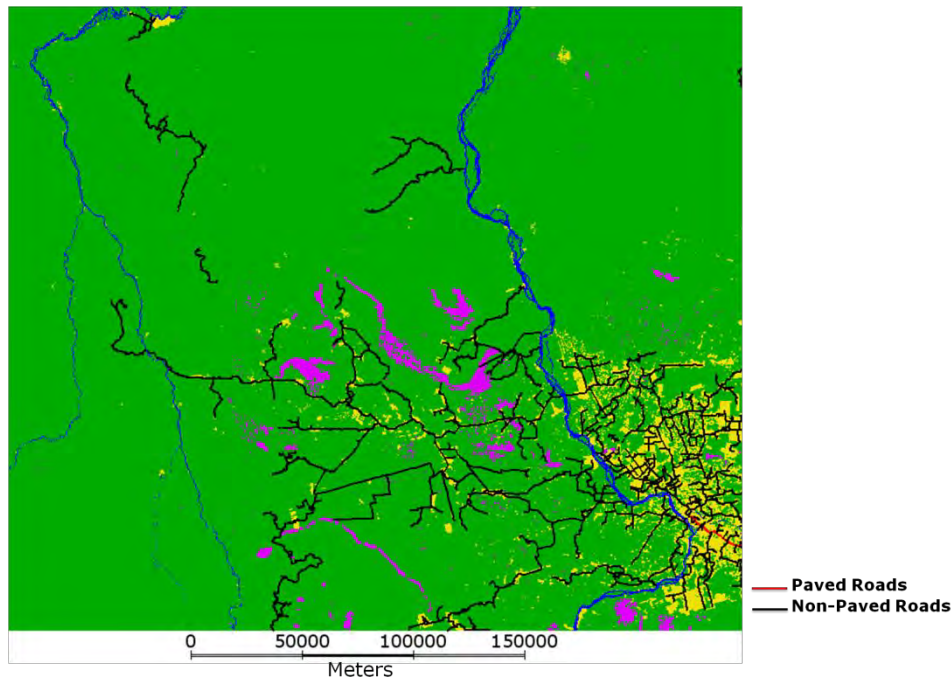


Figure 4.4 – Roads Network.

Source: Adapted from Amaral et al. (2006; 2007), Escada et al. (2005; 2007), Pinho et al. (2010), and Vieira et al. (2004).

The rivers form a network widely for transportation and flow of production in the region. Thus, they also play an important role in deforestation process, mainly during the flood season, when the condition of roads becomes precarious. Figure 4.5 illustrates the rivers network used in the development of the deforestation model. The largest rivers were extracted from PRODES data, and the smallest were selected, according to their importance to the transportation in the region, from the digital data provided by the National Water Agency (ANA<sup>4</sup> – [www.ana.gov.br](http://www.ana.gov.br)).

<sup>4</sup> Agência Nacional das Águas (in portuguese)

The airstrips (Figure 4.5) are used to connect remotest areas, and they are mainly used by big farmers. In the deforestation model developed, this network does not exert a direct influence over the deforestation process, but represents a potentiality idea, where each airstrip increases the influence of the others *circulation networks* surrounding it. The airstrips data used (AMARAL et al., 2006) was collected in 2004, and we do not have a multi-temporal data. Thus, in order to increase the dynamics of it, we consider that 20% of the airstrips already exist in the beginning of the simulation, and at each year, we enables more 20% until 2004, when all of them are enabled. However, some of the airstrips are located inside the protected areas. Thus, we consider that after the creation of these protected areas, they are disabled.

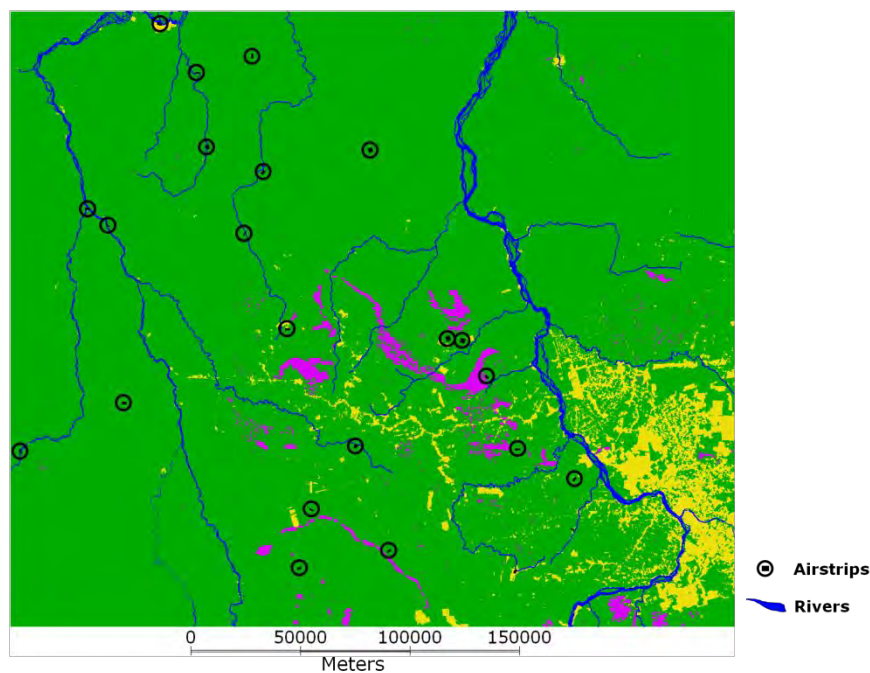


Figure 4.5 – Rivers and Airstrips.

Source: Adapted from Amaral et al (2006), ANA (2011) and INPE (2011).

In an attempt to halt deforestation in the region, which has experienced highest deforestation rates, in comparison to the rest of the Brazilian Amazon, in the last decade (ESCADA et al., 2005), the Brazilian government, through the Ministry of the Environment (MMA<sup>5</sup> – [www.mma.gov.br](http://www.mma.gov.br)), has developed a conservation policy framework. The basis for this framework was a mosaic of conservation units (UC<sup>6</sup>),

<sup>5</sup> *Ministério do meio ambiente* (in portuguese)

<sup>6</sup> *Unidades de conservação* (in portuguese)

presented in Figure 4.6, which was established as the National System of Conservation Unities - SNUC<sup>7</sup> (Federal Law number 9.985, July 18, 2000) – (IBAMA, 2000; IBAMA, 2011). According to the SNUC, the conservation unities are divided in two groups: “*Integral Protection Conservation Units*” and “*Conservation Units for Sustainable Use*”. In the *Integral Protection Conservation Units* is not allowed any type of land use. The *Conservation Units for Sustainable Use* is less restrictive, allowing some types of land use, and thus exerts a weaker attenuation of the deforestation process than the other group.

Another class of protected areas is the Indigenous Lands (TI<sup>8</sup>), under the Federal Government jurisdiction, through the National Indian Foundation (FUNAI<sup>9</sup> - [www.funai.gov.br](http://www.funai.gov.br)). These protected areas exert attenuation similar to that exerted by the *Conservation Units for Sustainable Use*, because they also allow some types of land use. It is illustrated in Figure 4.6.

In the deforestation model developed, we consider both UC and TI as protected areas. Thus, based on their land use restrictions and history, we have established a hierarchy, in order reproduce the different restriction levels. It was defined as follow:

- **Level 1:** *Integral Protection Conservation Units*.
- **Level 2:** *Conservation Units for Sustainable Use*, except the “*APA Triunfo do Xingu*”, which presents less restrictions of land use; and the *Indigenous Lands*, except the “*TI Apyterewa*”, which is described above, in **Level 3**.
- **Level 3:** *TI Apyterewa*. According to Amaral et al. (2006) and Vieira et al. (2004), this TI presents a longer occupation history. Thus, due to this history, we consider that it is less restrictive than the others.
- **Level 4:** *APA Triunfo do Xingú*, which is less restrictive than the others *Conservation Units for Sustainable Use*.

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<sup>7</sup> *Sistema Nacional de Unidades de Conservação* (in portuguese)

<sup>8</sup> *Terras Indígenas* (in portuguese)

<sup>9</sup> *Fundação Nacional do Índio* (in portuguese)

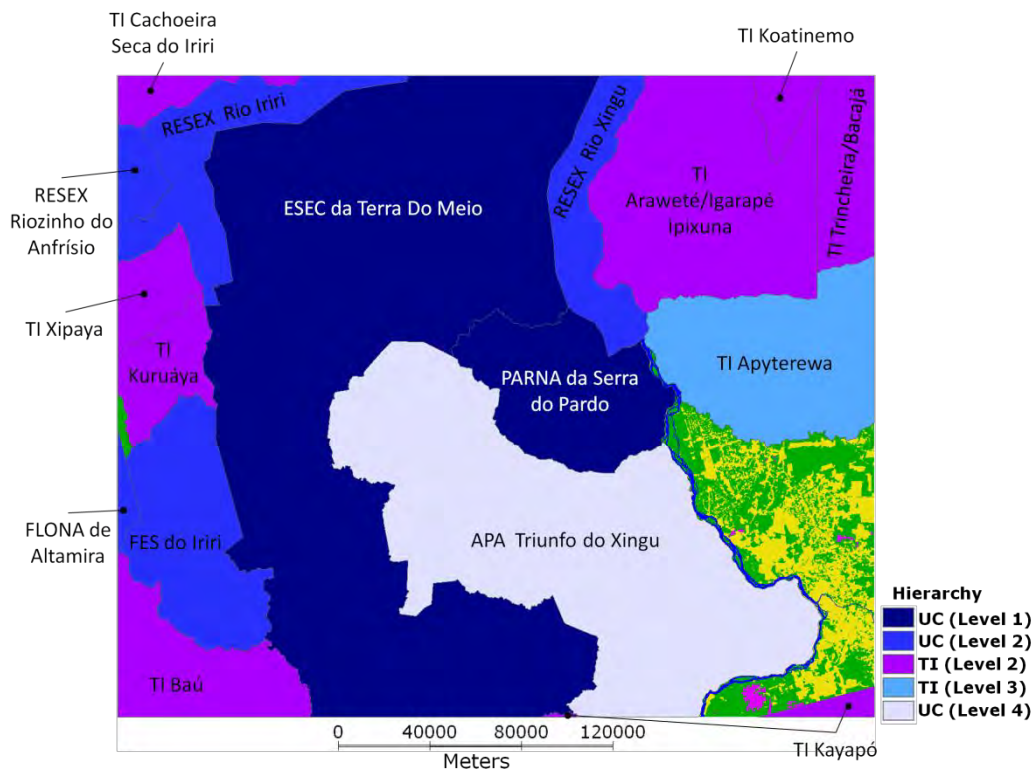


Figure 4.6 – Hierarchy considered for the protected areas (Conservation Unities and Indigenous Lands).

Source: Adapted from IBAMA (2011) and FUNAI (2011)

Spatial units of population (Urban seat, villages, districts and human settlements), which we call places, are considered small “control centers” of the deforestation process. They represent an idea of potentiality, amplifying the influence of the *circulation networks* surrounding them. This influence is discussed in more details in Section 4.2. Figure 4.7 illustrates the human settlements data used. These data were also collected in some field works made by INPE researchers (AMARAL et al., 2006, 2007; ESCADA et al., 2005, 2007; PINHO et al., 2010; VIEIRA et al., 2004). Each point representing a place has only one parameter that represents its hierarchical level. Thus, places at a higher hierarchical level exert a higher influence than that at a lower hierarchical level. These levels are: **Level 1 (Urban Seat)**, **Level 2 (Districts)**, **Level 3 (Villages)**, and **Level 4 (Human settlements)**.

The National Institute for Colonization and Agrarian Reform (INCRA<sup>10</sup>) has created some settlement projects (PA<sup>11</sup>) in the region, in order to promote an agrarian reform. In the deforestation model developed, these PA represent an idea of potentiality,

<sup>10</sup> Instituto Nacional de Colonização e Reforma Agrária (in portuguese)

<sup>11</sup> Projetos de Assentamento (in portuguese)



amplifying the influence of the *circulation networks* located inside them, and thus, intensifying the deforestation process in these areas. Figure 4.7 illustrates these areas.

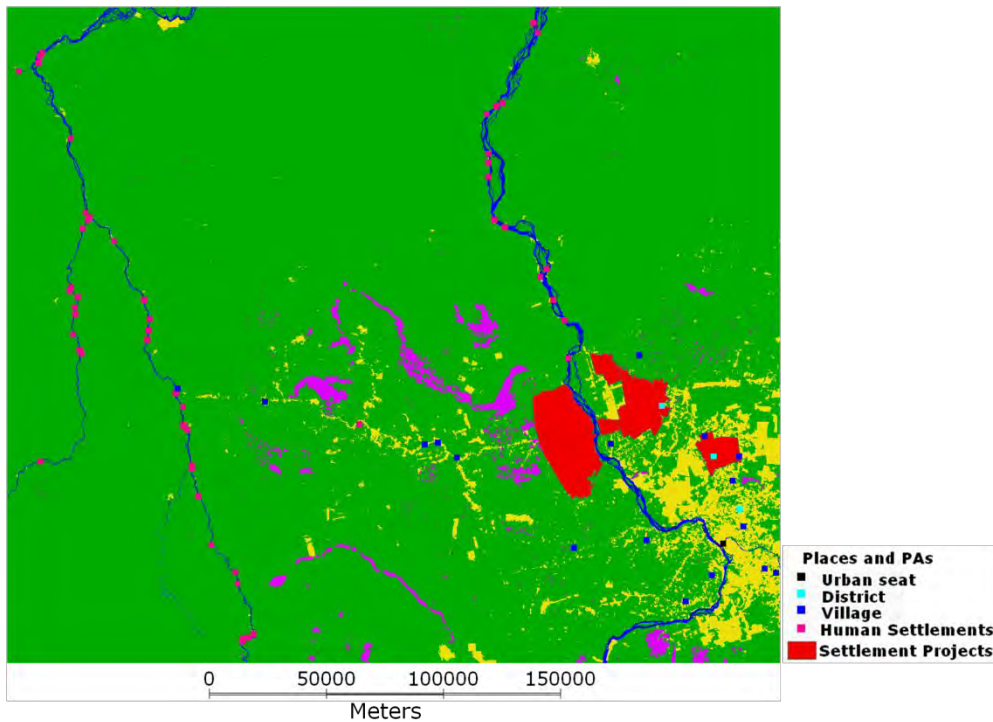


Figure 4.7 – Human settlements and settlement projects.  
Source: Adapted from Amaral et al (2006) and INCRA (2011).

## 4.2. The Deforestation Model

A CA-based deforestation model was developed based on the processes described in Amaral et al. (2006). Basically, it aims to simulate the evolving deforestation patterns, between the years 2000 and 2009, in the described area, taking into account the influence of *circulation networks* that have evolved over time. It is important to keep in mind that the main purpose of this model is to demonstrate the potential of the *Dynamic Neighborhoods* concepts and its algebraic formalism, by verifying its impacts in a model developed based on empirical data over a real world setting. Thus, we must emphasize that the deforestation model can be very much improved, in order to better reproduce the reality, but this is not the focus of this work.

The basis for the modeling is building an estimate of the potential proportion of deforested area in each cell. Basically, this estimate is made weighting each cell considering:

1. Its relative position to an entry point (connection node) of a *circulation network* or a place;
2. The presence of Conservation Unities (UC), Indigenous Lands (TI) or Settlement Projects (PA).

In this model we contemplate the evolution of *circulation networks* by acknowledging new roads that are built, road segments that can no longer or temporarily be used, improvements on roads pavement and the opening and closing down of airstrips. In addition, the seasonality was dealt within the model, by changing the mobility and the connectivity patterns when the *circulation networks* are operating either in dry or flood season. The dynamics associated with these evolving *circulation networks* produce, from a modeler's perspective, the need for changing the neighborhoods structures and re-evaluating the relations weight.

As previously mentioned, the spatial units of population (places) are considered small "control centers" of the deforestation process. In this sense, the connectivity amongst them represents an idea of potentiality for a deforestation event to occur, amplifying the *circulation networks'* influence in the territory. This influence varies according to the hierarchical level of each one of these places. Based on the places data presented in Figure 4.7, two neighborhoods were created over the grid of cells, an intersection neighborhood and a buffer neighborhood, both described below:

- Intersection neighborhood: represents the relationship between the grid of cells and the points representing the places, as shown in Figure 4.8 (a). Each cell has, as its neighbor, the points located inside it. The relation is not weighted.

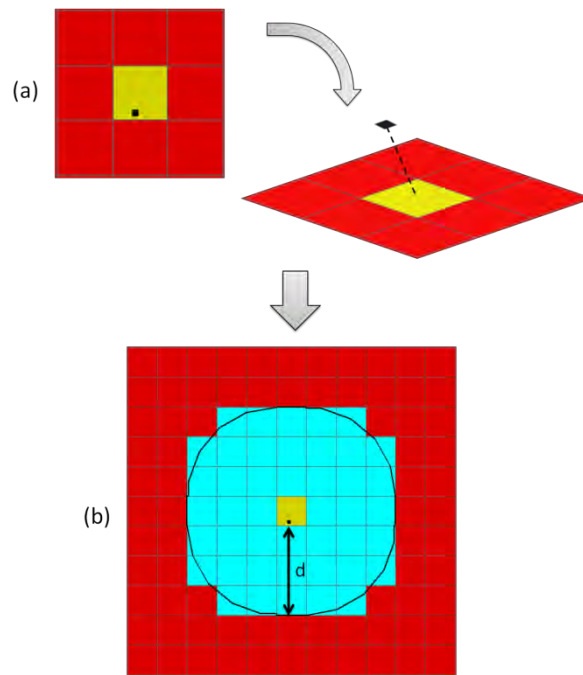


Figure 4.8 – Neighborhoods generated to represent the influence of places and airstrips: (a) Intersection relationship; (b) Buffer neighborhood.

- Buffer Neighborhood: it was set up based on a distance of influence of each place. For each place, a distance of influence is defined, based on its hierarchical level. The weight  $w_p$  of each relation is defined based the inverse of the squared distance ( $d_p$ ) from the cell intersected by the place to the neighbor, as shown in equation 4.1.

$$— \quad (4.1)$$

The conservation unities and the Indigenous Lands were considered protected areas, once both have restrictions on land use. In the deforestation model developed, these areas play an attenuation role for the deforestation. Inside them, the influence of the circulation networks was decreased. In the “fully protected” conservation unities is not allowed any land use activity, thus representing a larger attenuation than the “sustainable use” ones and the Indigenous lands, which allow some types of land use activities. The attenuation intensity varies according to the hierarchical level of each protected area. In the neighborhood created between the protected areas and the cells,

each cell was connected to the conservation unit that has the largest intersection area, as shown in Figure 4.9. This relation is not weighted.<sup>12</sup>

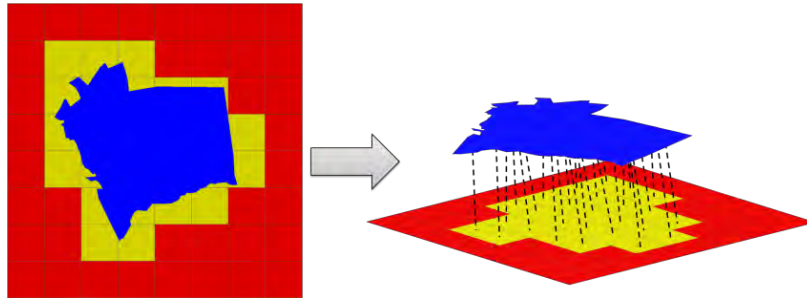


Figure 4.9 – Neighborhood relation between the polygons representing the cells and the polygons representing the UC, PA and TI.

The settlement projects represent, even as the places, a potentiality idea, increasing the influence of all the circulation networks located in its territory. The neighborhood relationship defined between the PA and the cells follow the same idea of UC and TI, connecting the cell to the polygon that has the largest intersection area, as shown in Figure 4.9.

The airstrips are used to connect remotest areas. In the developed deforestation model, this type of node does not have a direct influence over a deforestation event, but represents, as well as the places and PA, a potentiality idea. Thus, the airstrips amplify the influence of roads and rivers located close to them. The neighborhood defined to represent the relation between the airstrips and cells are the same used in the case of places, shown in Figure 4.8, but in this case, the weight of each cell is calculated through the equation below:

$$— , \tag{4.2}$$

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<sup>12</sup> It is important to notice that we can see conflicting land uses in all types of conservation units. For this experiment, in order to keep its complexity smaller, with focus on the changes derived from direct influence of the circulation networks, we did not work on a fuzzy parameterization of the conservation unities' attenuation property, what can be done in future models.

where

- $iuc$  is the influence of conservation unities over the cell connected to the airstrip;
- $ip$  is the influence of places, that is multiplied by the weight  $w_p$  of the corresponding place, thus varying according to it;
- $iti$  is the influence of TIs;
- $ipa$  is the influence of PAs;
- $d_a$  is the distance from the cell intersected by the airstrip to the neighbor one.

The roads exert the largest influence on this experimental deforestation model, once it is the most used transportation network. We consider that it is a direct influence, allocating 85% of the total deforestation demand around them. Based on the roads network presented in Figure 4.4, two neighborhoods were created over the grid of cells, an intersection-based neighborhood and a buffer, both described below:

- Intersection-based neighborhood: represents the relationship between the cells and the lines representing the roads, as shown in Figure 4.10 (a). Each cell has, as its neighbor, the lines intersecting it. In this case, the relations are not weighted;
- Buffer neighborhood: it was set up from an area of influence defined around each cell intersected by a road segment. For each cell, a distance was defined representing the distance of influence of the road that intersects it in the surrounding area, based on the attributes of the considered road, even as the influence of places, UC, PA, TI and airstrips. In addition, some secondary roads randomly chosen had its influence increased, in order to reproduce the big famers' behavior, which in general are located in remotest areas. Thus, all the cells located inside this area was considered neighbors from the one intersected by the considered road segment, as shown in Figure 4.10 (b). The weight  $w_r$  of each neighbor is calculated through:

$$—, \quad (4.3)$$

where

- $pf$  is the “Paving factor”, i. e., how much the paving of a road increases its influence;

- $sf$  is a value that we call “Secondary factor”, which represents much to increase the influence of the randomly selected secondary roads;
- $ia$  is the influence of airstrips;
- $d_r$  is the distance from the cell intersected by the road segment to the neighbor one.

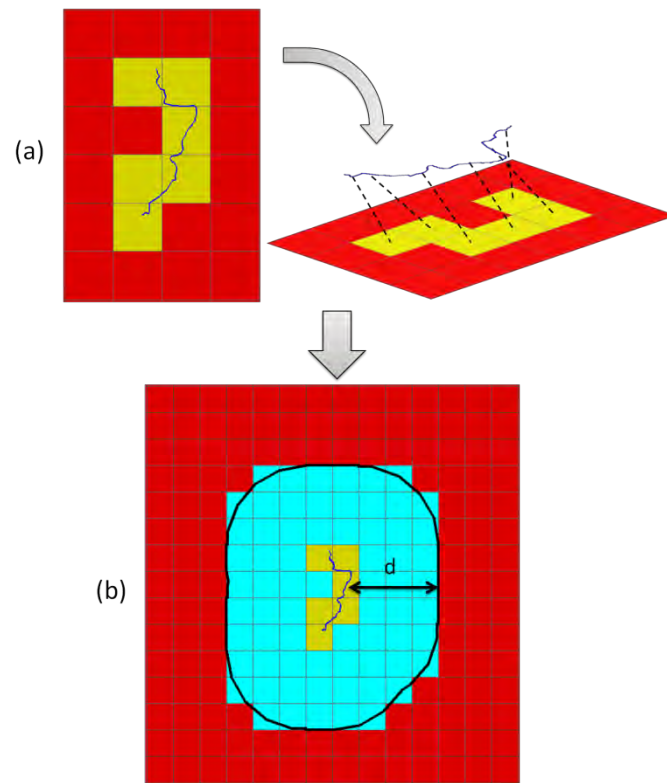


Figure 4.10 – Neighborhoods generated from roads and rivers: (a) Intersection-based relationship; (b) Buffer neighborhood.

For this study area over the established period, we took the rivers network as not exerting as much influence as that of the roads network. In addition, its influence depends on the presence of another modal node on the *circulation network* (an airstrip or a road segment) or a place. Despite the rivers exert a lower influence, was considered that it is also a direct influence, allocating 15% of the total deforestation demand around them. Thus, based on the rivers network presented in Figure 4.5, we set up two neighborhoods similar to that defined for the roads, show in Figure 4.10. Once the influence exerted by rivers depends on the presence of another modal node on the *circulation network*, or a place, the buffer around it was constructed only if the cell intersected by the rivers (the central cell of the buffer) is in the buffer of a road, airstrip or place. The weight ( $w_{ri}$ ) of each neighbor cell in this buffer is defined through the

equation 4.4, where  $d_{ri}$  is the distance from the cell intersected by a river to the neighbor cell.

— (4.4)

Even though the temporal resolution of the PRODES deforestation data is annual, we have considered a semiannual resolution to our deforestation model, in order to reproduce the effects of the seasonal processes of the region. Basically, we have divided the year in two periods: the *dry season*, comprehended between May and September; and the *flood season*, comprehended between November and March, being April and October transition months, according to CPTEC/INPE (FISCH et al, 2010). During the dry season, all the *circulation networks* work as described above. But during the flood season, due to the large volume of rain, the roads located closest to rivers become unusable, being deactivated in the model by making use of the proposed operations defined for dealing with dynamic neighborhood in this work.

Since May 2004, INPE has been providing monthly deforestation rates through the DETER<sup>13</sup> (Real Time Deforestation Detection System) project (INPE, 2011b; INPE, 2008). It is important to note that, as DETER uses optical remote sensing images to monitor the deforestation, in a month with no deforestation detected, not necessarily no deforestation happened. It happens because in some months, especially during the flood season, it is impossible to acquire images without cloud cover. Thus, in order to determine how much deforestation occurs in each season in the deforestation model developed, we analyzed DETER data for three years: 2005, 2006 and 2008 (shown in Appendix A). By taking an average of deforestation rates for each season in the three years, was defined that 89% of the annual deforestation demand occurs during the dry season, and 11% during the flood season.

Basically, the operation of the deforestation model developed can be summarized in the following steps (Figure 4.11):

- 1 – Set up the *initial state* of the system;
- 2 – Starts the semiannual cycle;

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<sup>13</sup> *Sistema de Detecção de Desmatamento em Tempo Real* (in portuguese)

- 2.1 – Calculate the *total area to deforest* in the year (Annually executed);
- 2.2 – Calculate the *area to deforest in the current season*;
- 2.3 – Allocation process (Executed for each cell in the buffer of roads and rivers);
  - a – Converts the “cell weight” in “quantity to change”;
  - b – Deforest cell;
- 2.4 – Report simulated outputs;
- 2.5 – Increment model time (semester = semester + 1);
- 2.6 – ***Reconfigure networks and its attributes.***

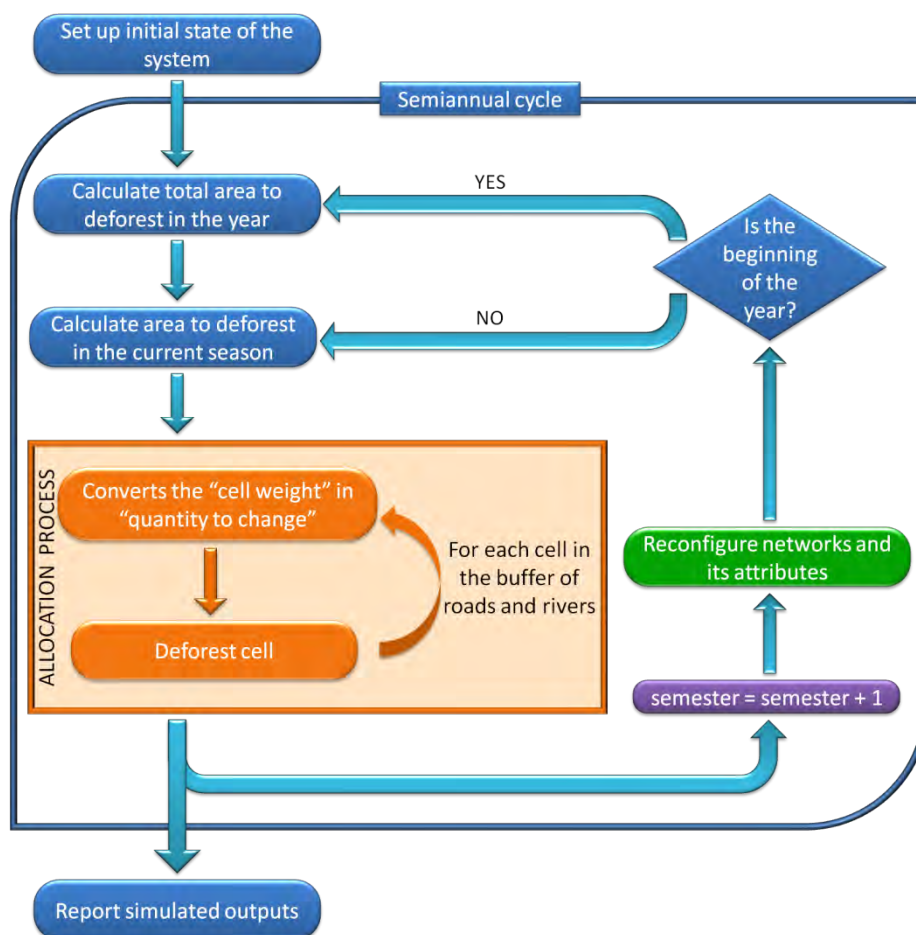


Figure 4.11 – Flowchart showing the main steps of the deforestation model developed. The Reconfigure step brings in it the main contribution of this work.

### Step 1 – Set up initial state of the system

Before start the simulation process, all the circulation networks’ attributes are initialized. It also loads the intersection-based neighborhoods and set up the buffers.

### Step 2 – Starts the semiannual cycle of the model



After all the initial state of the system was set up, the semiannual cycle was started.

### **Step 2.1 – Calculate total area to deforest in the year**

This step is executed only if the current time is the beginning of the year. Basically, in this step the total forest area is calculated, by summing the forest area of all the cells and taking the percentage demanded to deforest. The annual deforest demand is a parameter of the model, which values are shown in the Appendix B.

### **Step 2.2 – Calculate area to deforest in the current season**

In this step, the seasonal area demanded to deforest is calculated, based on the percentage demanded to the current season and the area calculated in the step 2.1.

### **Step 2.3 – Allocation process**

This step constitutes a loop, which transverse the buffer neighborhood of the roads and rivers allocating the deforest demand calculated for the current season. For each cell visited, it executed the following steps:

#### **Step 2.3(a) – Converts the “cell weight” in “quantity to change”**

In order to allocate the deforestation proportionally to the influence applied by the circulation networks over the cell being deforested, we consider the cell weight in the buffer neighborhood of roads and rivers as its “potential for change”. If the cell forest area represents less than 80% of its total area, we convert the cell weight to a scale between 0.005 (0.5% of the cell forest area) and 0.2 (20% of the cell forest area), otherwise it is converted to a scale between 0 (0% of the cell forest area) and 0.02 (2% of the cell forest area). This scaling is done through:

$$\text{—————}, \quad (4.5)$$

where

- $p_{change}$  is the percentage of the cell forest area which will be deforested;
- $maxDef$  is the maximum value which can be deforested (0.2 or 0.02, depending on the cell forest area, as described above) in the current time step;
- $minDef$  is the minimum value which can be deforested (0.005 or 0, depending on the cell forest area, as described above);

- $w_{max}$  is the maximum weight found in the buffer of the considered network (river or road);
- $w_{min}$  is the minimum weight found in the buffer of the considered network;
- $w$  is the cell weight.

### **Step 2.3(b) – Deforest cell**

In this step, the cell forest area is effectively decreased, according to the value calculated in the previous step.

### **Step 2.4 – Report simulated outputs**

After the allocation process is finished, the model save the simulated results in the database, generating a map with the spatial distribution of the deforestation for the current season.

### **Step 2.5 – Increment model time (semester = semester + 1)**

In this step the model timer is increased.

### **Step 2.6 – Reconfigure networks and its attributes**

In this step, all the neighborhoods are reconfigured through the use of the *Dynamic Neighborhoods* concepts, proposed in this work.

## **4.3. Simulation results**

The main goal of the deforestation model developed is to demonstrate the potential of the *Dynamic Neighborhoods* concepts and tests its implementation. To accomplish this, we made four modeling experiments, running the deforestation model simulation considering different configurations and dynamics for the *circulation networks*. In the first one, we do not use the *Dynamic Neighborhoods* concepts, in order to compare its results with the others, which use the DN concepts. Through this comparison, we aim to demonstrate the influence of the different neighborhoods configurations and its dynamics in the simulated output. It is important to notice that all the experiments consider the influences of the places (Urban seat, villages, districts and human settlements), conservation unities, settlement projects, and indigenous lands, as described in Sections 4.1.1 and 4.2. The analyses will be made through the attribute “Percentage of Deforestation”. These experiments are described below:

- **Experiment 1:** The model simulation was run considering only the roads network, without the *Dynamic Neighborhoods* concept. We have created the neighborhoods based on the existing roads network in 2000 (Initial State of the system), and it does not change during the simulation. The influence of the rivers and airstrips networks was not considered, even as the seasonality effects. Thus, the step 2.6 of the model was not executed, and the whole deforestation was allocated in the cells located in the buffer of roads. The temporal resolution of the model was annual, instead of the semiannual resolution of the experiments 3 and 4, due to the absence of the seasonality effects. Figure 4.12 shows the initial state of the system, even as the roads network considered in the model.
- **Experiment 2:** The model was run considering only the roads network, but using the *Dynamic Neighborhoods* concept, in order to reproduce the dynamics of roads. It also does not consider the influence of the rivers and airstrips networks, neither the seasonality effects. Thus, due to the absence of the seasonality effects, in this experiment, the temporal resolution of the model was also annual. The only difference between this experiment and the first one is the changes occurring in the roads network through the time, i. e., in this experiment, the step 2.6 of the model was executed. The initial state of the system is shown in Figure 4.12.

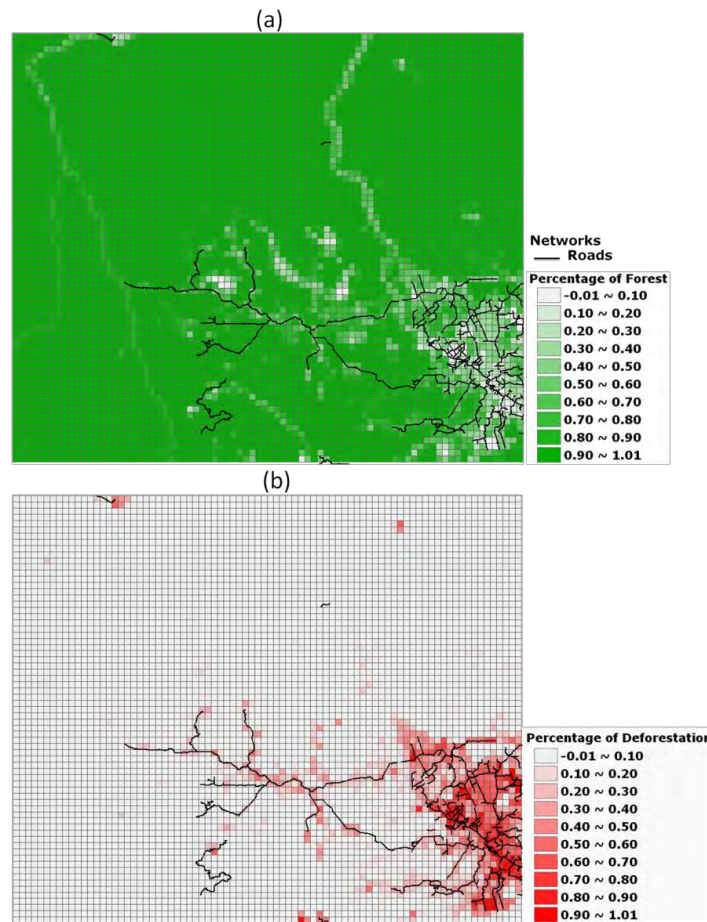


Figure 4.12 – Initial state of the system for the Experiments 1 and 2. Attributes: (a) Percentage of forest and (b) Percentage of deforestation.

- Experiment 3:** In this experiment, the model was run considering the influence of both, roads and rivers. As we come to consider the influence of the rivers network, in this experiment, the seasonality effects was also considered, deactivating roads' segments located closest to rivers during the flood season, and activating them during the dry season. Figure 4.13 shows the initial state of the system (a), and the seasonality effects over the roads (b). It is important to see that there are many segments deactivated. It happens because of its size. In future works, it will be broken, in order to better reproduce the reality, but this is not the focus now. In this work, just focus on the impact of this dynamics, causing changes in the simulated deforestation patterns. The initial state of the attribute “percentage of deforestation” is the same of the experiments 1 and 2, shown in Figure 4.12.

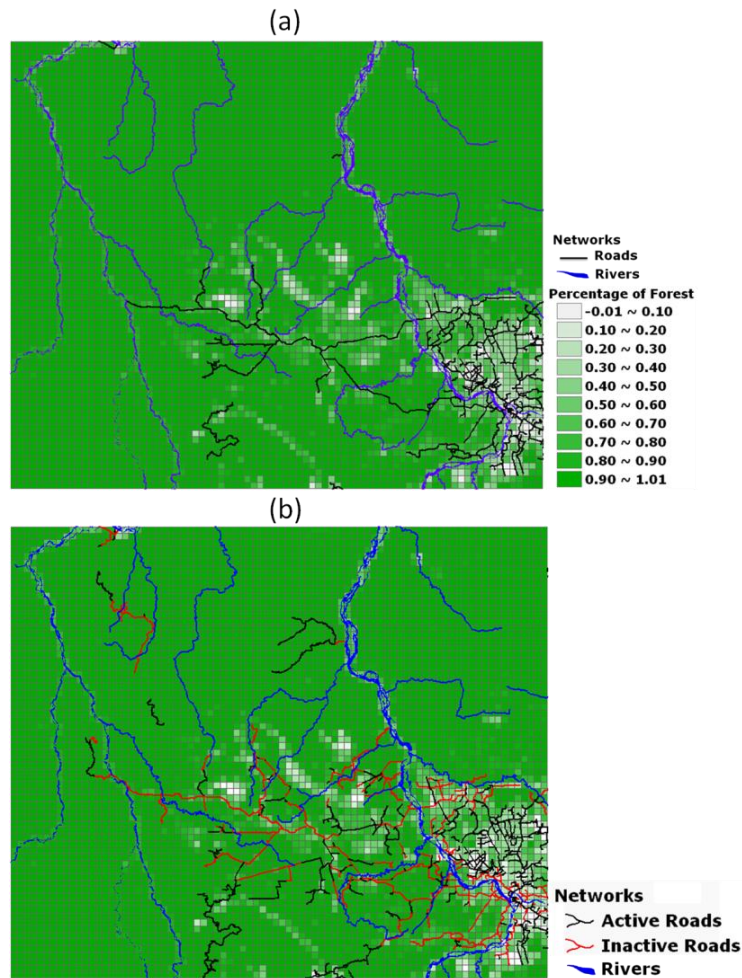


Figure 4.13 – Initial state of the system for the experiment 3 (a) and seasonality effects over roads (b).

- **Experiment 4:** In this experiment, the model was run considering the influence of all the *circulation networks* (roads, rivers and airstrips), and its dynamics. These dynamics are similar to the experiment 3, but adding the airstrips' influence, as described in the Section 4.2. Figure 4.14 shows the initial state of the system for this experiment.

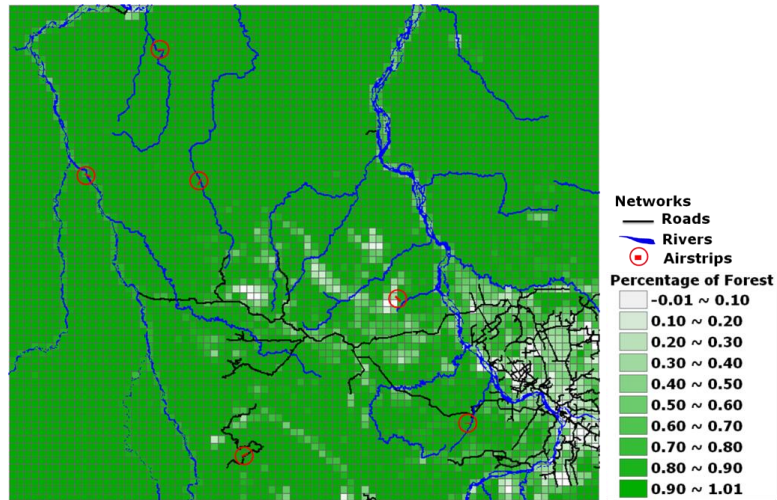


Figure 4.14 – Initial state of the system for the experiment 4.

Figure 4.15 shows a comparison between the simulated results of the experiments 1 and 2. These experiments have presented simulation results furthest from the reality, but in the comparison between them, it is important to notice some differences caused by the addition of the DN concepts. In the experiment 2, this addition has led to the occurrence of deforestation in some places where it does not occur in the experiment 1, even as to most spread deforestation patterns in other regions. It happens due to the evolution of the roads during the simulation process, with new segments being created, another existing ones being paved and with the creation of new conservation unities and settlement projects. In Figure 4.15, the main differences between these two experiments are circled.

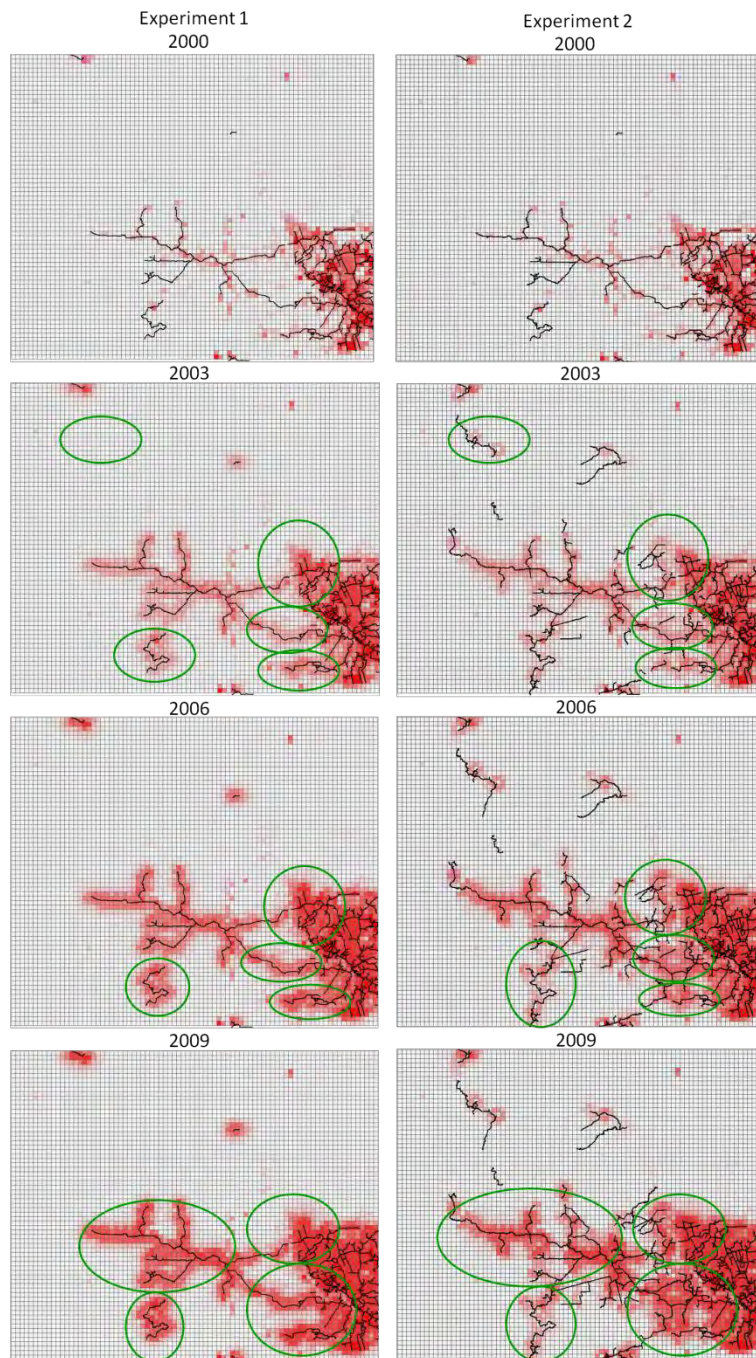


Figure 4.15 – Comparison between deforestation patterns generated in Experiments 1 and 2.

Figure 4.16 shows a comparison between the simulated results of the experiments 2 and 3. It is important to notice that, with the addition of the rivers network, new deforestation foci appear along the rivers, even as along some roads. In addition, some deforestation patterns become more spread, and others become narrower.

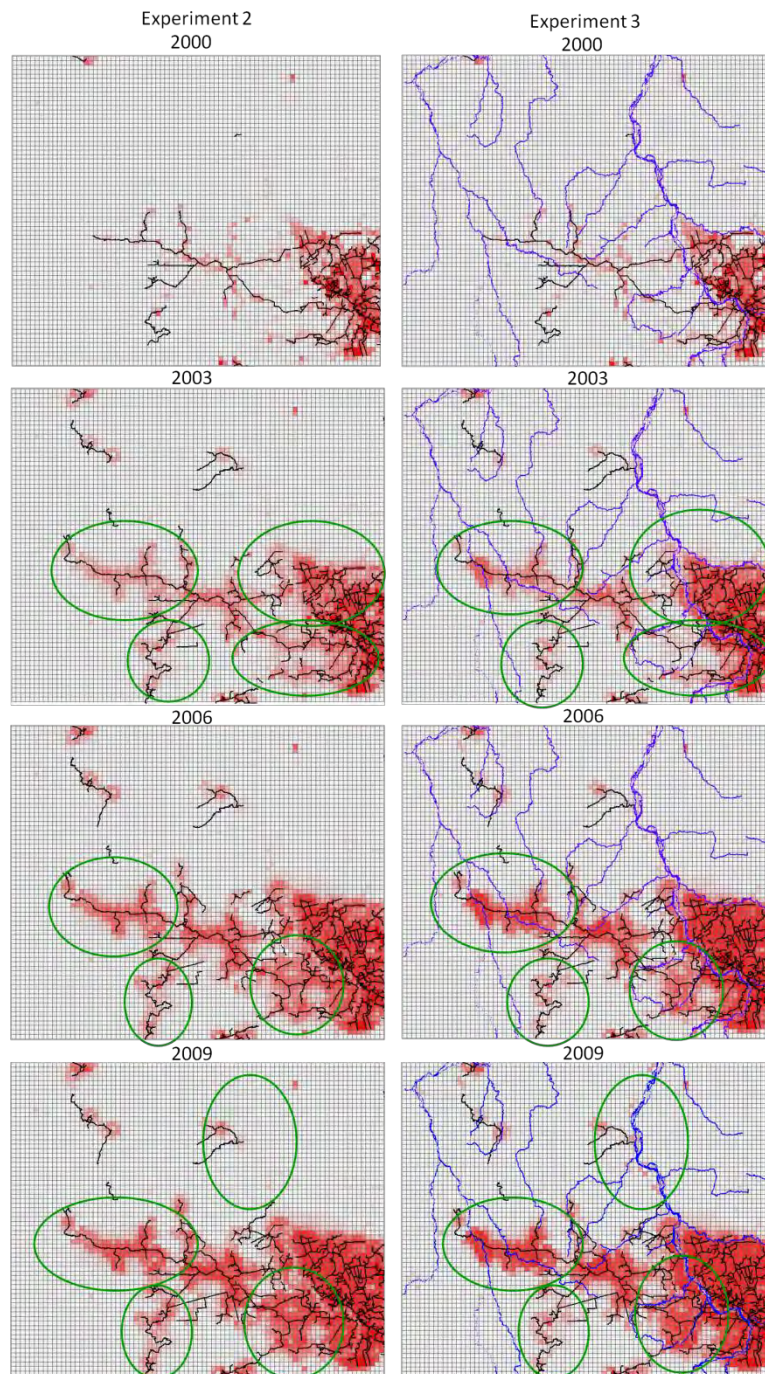


Figure 4.16 – Comparison between deforestation patterns generated in Experiments 2 and 3.

Figure 4.16 shows a comparison between the simulated results of the experiments 3 and 4. Since the influence exerted by the airstrips is not a direct one, the differences between the deforestation patterns generated by these experiments are more subtle. In the experiment 4, with the increase of the influence of some roads located closest to the airstrips, the deforestation patterns around some of these roads become more condensed.



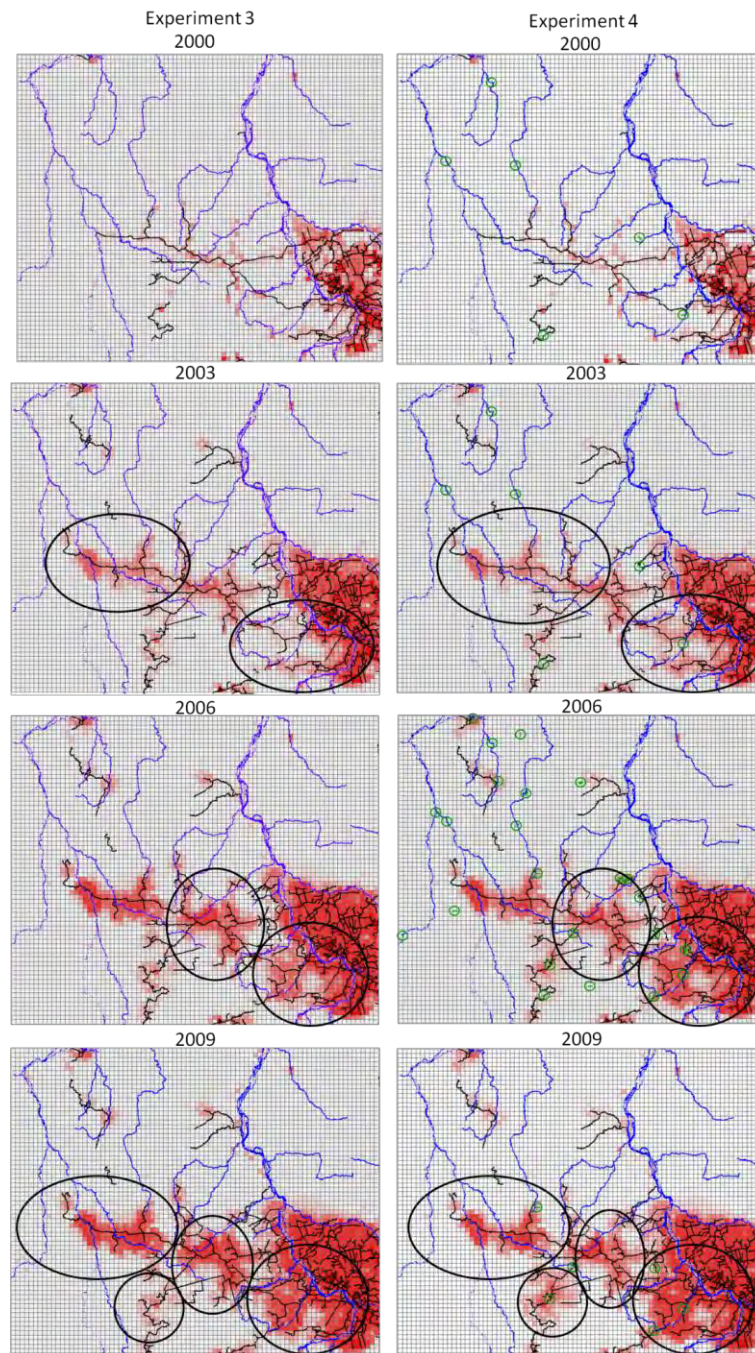


Figure 4.17 – Comparison between deforestation patterns generated in Experiments 3 and 4.

Through these experiments, we can see that different neighborhoods configurations and dynamics can generate different simulated patterns in a CA-based model. It is possible to notice that, the reconfiguration of the neighborhoods structures during the life cycle of a model can introduce new possibilities for changing its simulated results. Thus, it is possible to notice that the DN concepts have a large potential for provide new perspectives to represent real world dynamics in CA-based models.

Figure 4.18 shows the real data and the deforestation patterns generated in the experiment 4. As previously mentioned, in this work, the focus is not to reproduce exactly the real deforestation patterns, and the model can be refined, in order to do this. However, it is possible to notice that, despite the generated deforestation patterns are not identical to the real data, in most areas the deforestation was correctly allocated. It demonstrates the potential of this deforestation model to be refined in future works to be able to better reproduce real deforestation patterns.

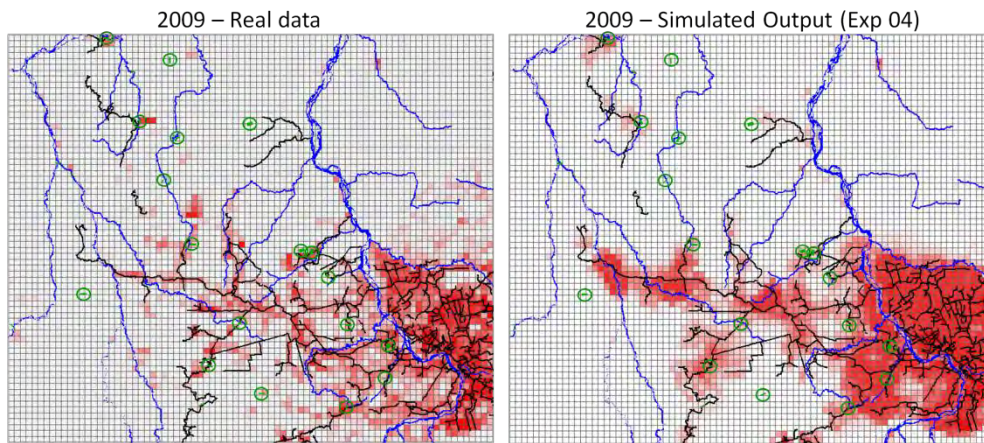


Figure 4.18 – Real Data and deforestation patterns generated in experiment 4.



## 5. CONCLUDING REMARKS

Several recent studies have demonstrated that the neighborhood configuration influences directly the outcomes of CA-based models. Once neighborhoods change over time, it becomes even more important for spatial dynamic modeling platforms. Modelers now can construct their models in such a way that they are able to cope with reconfiguration of neighborhood structures at runtime. This new feature expands the universe of problems which can be modeled.

We presented, in this work, a formal model, based on algebraic definitions over graph structures, to cope with neighborhood structures that can be reconfigured at runtime in CA-based models. In addition, we have defined a typology of modeling situations where, from a modeler's perspective, a neighborhood structure reconfiguration is needed. The formal model proposed was implemented in the TerraME platform, allowing for better representing the dynamics of real world networks and relations in computational CA-based models.

Through the implementation that has been provided, we developed a deforestation model, where the Dynamic Neighborhoods concept was used, as a *proof-of-concept* experiment. The results of this model have demonstrated that the DN concepts, presented in this work, have a large potential for providing new perspectives to represent real world dynamics in CA-based models. Through the comparison between 4 experiments made with this deforestation model, considering different neighborhoods configurations and dynamics in each one, we also, as others before, have empirically showed that the configuration and dynamic of neighborhoods have direct impact on CA-based models' simulated results.

The implementation of the DN concepts into the TerraME platform has extended the framework to deal with a new class of problems, in which the spatial dynamics under observation implies neighborhoods structures that change over time, needing runtime reconfiguration to keep the model's hypotheses consistent over its life cycle.

Finally, in order to advance the proposal presented in this dissertation, we have to complete the implementation with some functions formally defined over here, but not implemented yet. In addition, we have to readdress the deforestation model, proposed here as a *proof-of-concept* experiment for computational mechanisms, in order to

explore the DN possibilities together with deforestation process scientists, by building a model with a better hypothesis framework, data and functions specification, and parameters extraction and calibration.

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## APPENDIX A: PARAMETERS OF THE PROOF-OF-CONCEPT MODEL – VALUES AND REASONS

The deforestation model developed as *proof-of-concept* received several values as parameters. This appendix describes these values and the reasons for choose them. These parameters are:

- **Annual Deforestation Demands:** It was defined based on the PRODES (INPE, 2011a) deforestation rates available for each year for the *São Félix do Xingú* municipality. These demands are presented in the following table:

Year	Deforestation Demand
2000	2.01%
2001	1.5%
2002	1.57%
2003	1.28%
2004	1.67%
2005	0.9%
2006	1.04%
2007	0.9%
2008	0.52%

- **Distribution of the deforestation demand:** It defines which portion of the deforestation demand should be allocated around each *circulation network*. It was defined based empirical tests and analysis of the spatial distribution of the deforestation provided by PRODES. As described in sections 4.1.1 and 4.2, the airstrips do not exert a direct influence over the deforestation. Thus, the deforestation was allocated only around the roads and rivers networks. The values used are presented in the following table:

Network	Demand
Rivers	85%
Roads	15%

- **Seasonal Deforestation Demand:** Despite the deforestation data provided by PRODES are annual, the deforestation model developed has a semiannual temporal resolution. In order to estimate the deforestation demand for each season (flood season and dry one), we analyzed the deforestation rates provided by the Real Time Deforestation Detection System (DETER/INPE) (INPE,

2011b) for 2005, 2006 and 2008 years, taking an average of the seasonal deforestation rates measured for these years, and then using this value as the deforestation demand for the corresponding season. The following table presents these data:

Year	Flood Season	Dry Season
2005	0.48%	99.52%
2006	1.92%	98.08%
2008	31.14%	68.86%
Average	11.18%	88.82%

- **Distances for the buffer around places:** Based on previous studies about the area considered for the deforestation model (AMARAL et al, 2006, 2007; ESCADA et al., 2005, 2007; PINHO et al, 2010; VIEIRA et al., 2004) and some empirical tests, we defined the following distances for the buffer around places, according to their hierarchical level:

Hierarchy	Distance
Level 1 (Urban seat)	30 km
Level 2 (Districts)	20 km
Level 3 (Villages)	10 km
Level 4 (Human settlements)	5 km

- **Influence of places:** It defines how each place amplifies the influence of the circulation networks, according to the hierarchical level of the corresponding place. The amplification factor for each hierarchical level is listed below:

Hierarchy	Amplification factor
Level 1 (Urban seat)	10%
Level 2 (Districts)	10%
Level 3 (Villages)	8%
Level 4 (Human settlements)	3%

- **Distances for the buffer around rivers:** Either based in previous studies about the considered area and some empirical tests, we defined, according to the hierarchy defined for this network , the following distances for the buffer around rivers:

Hierarchy <sup>14</sup>	Distance
Primary	10 km
Secondary	8 km

- **Distances for the buffer around roads:** It defines the distance of influence of the roads, i. e., the size of the buffer around them. Based on the previous studies about the area, we defined a hierarchy, where the most important roads were classified as “primary” and the others as “secondary”. Thus, we defined the following distances:

Hierarchy	Distance
Primary	15 km
Secondary	12 km

- **Increment by paving:** It defines how much to increment the influence (distance and weight) of a paved road segment.
  - **Value:** 30%.
- **Percentage of roads to pave:** It defines the percentage of road segments to be paved during each year.
  - **Value:** 5%.
- **Probability to increase the buffer around secondary roads:** It defines the probability to increment the influence (distance and weight) around a secondary road, in order to reproduce the big farmers’ behavior, as describe in section 4.2.
  - **Value:** 40%.
- **Secondary Factor:** It defines how much to increment the influence of the chosen secondary roads.
  - **Value:** 40%.
- **Distance to disable roads:** Defines the distance between a road segment and a river to disable it during the flood season, i. e., if the distance between a road segment and the closest river is smaller than the value defined for this parameter, this segment becomes impassable during the flood season.
  - **Value:** 5 km.
- **Percentage of airstrips initially enabled:** The percentage of airstrips that is initially enabled.
  - **Value:** 20%.

---

<sup>14</sup> This hierarchy was not defined according to Hydrological theories, but considering the importance of each river to the region.



- **Influence of airstrips:** It defines how each airstrip amplifies the influence of the other circulation networks surrounding it.
  - **Value:** 20%.
- **Distance for the buffer around airstrips:** It defines the distance of influence of the airstrips, i. e., the size of the buffer around them.
  - **Value:** 8 km.
- **Attenuation factor of the Protected Areas (Conservation Unities and Indigenous Lands):** It defines how each Protected Area attenuates the influence of the circulation networks located inside it. It was defined according to the hierarchical level of the corresponding Protected Area, based on the hierarchy presented in the section 4.1.1. The attenuation factor for each hierarchical level is listed below:

Hierarchy	Amplification factor
Level 1	95%
Level 2	70%
Level 3	30%
Level 4	5%

- **Amplification factor of the Settlement Projects (PA):** It defines how each PA amplifies the influence of the circulation networks located inside it.
  - **Value:** 30%.

## APPENDIX B: THE USAGE OF DYNAMIC NEIGHBORHOOD CONCEPTS IN EACH EXPERIMENT

This appendix describes the usage of the Dynamic Neighborhood (DN) concepts in each one of the experiments described in section 4.3. The excerpts of source code where the DN concepts were used are shown in Appendix C.

- **Experiment 1:** As described in section 4.3, we did not use the DN concepts in this experiment.
- **Experiment 2:** In this experiment, the DN concepts were used to reconfigure the buffer neighborhood around the roads before to simulate each time step. The reconfigure function is executed before each time step (1 year). When new roads are created, the reconfigure function creates the buffer around them, and when the roads are paved or a Protected Area is created, for example, it reconfigures the existing buffer, in order to reproduce the influence of it. The source code of this operation is shown in Appendix C: Code 1 presents the *Neighborhood Law* of the buffer around roads, and Code 5 presents the *Reconfigure* function for this buffer, which is based on the *Neighborhood Law* of the Code 1.
- **Experiment 3:** In this experiment, the DN concepts were used not only to reconfigure the buffer around roads, but either to that around rivers and to reproduce the seasonality effects (which reflect in the buffer around roads). The reconfigure function is executed before each time step, which in this case is semiannual. The source code of this operations are shown in Appendix C: Code 1 presents the *Neighborhood Law* of the buffer around roads; Code 4 presents the *Neighborhood Law* of the buffer around rivers; Code 5 presents the *Reconfigure* function for the buffer around roads; and Code 7, the *Reconfigure* function for the buffer around rivers.
- **Experiment 4:** This experiment, as presented in Section 4.3, uses the whole model described in Section 4.2. Thus, the DN concepts are used in the buffer around roads, rivers and airstrips. All the operations used in Experiment 3 were used, and with the addition of the airstrips to the model. Thus, the *Reconfigure* functions of all the networks were executed before to start each semiannual time step. The source code of the functions used to reconfigure the buffer around airstrips is shown in Appendix C: Code 3 shows the *Neighborhood Law* for the

buffer around Airstrips, and Code 6 shows the *Reconfigure* function for this buffer.

## APPENDIX C: SOURCE CODE OF THE NEIGHBORHOODS RECONFIGURATION IN THE *PROOF-OF-CONCEPT MODEL*

This Appendix presents excerpts of the source code of the deforestation model where the Dynamic Neighborhood concepts were used.

### Code 1 – Neighborhood Law of the Buffer around roads

```
-- Metatable for the neighborhood law of the buffer around the roads
BuffRoadsLaw_ = {
  filter = function(self, cell, neigh)
    local distNeighborhood = cell:getNeighborhood(self.names.dist);
    local roadNeighborhood = cell:getNeighborhood(self.names.roads);
    local UCsNeighborhood = cell:getNeighborhood(self.names.UCs);
    local TIsNeighborhood = cell:getNeighborhood(self.names.TIs);
    local PAsNeighborhood = cell:getNeighborhood(self.names.PAs);

    if((not roadNeighborhood:isEmpty()) and
      (distNeighborhood:isNeighbor(neigh))) then

      local distance = distNeighborhood:getNeighWeight(neigh);

      roadNeighborhood:first();
      local road = roadNeighborhood:getNeighbor();

      self.pavingFactor = 1;
      self.secondaryFactor = road.incBuffSec;
      self.UCFactor = 1;
      self.infPlaces = 1;
      self.TIFactor = 1;
      self.PAFactor = 1;
      self.airstripFactor = 1;

      if(road.pave == "paved") then
        self.pavingFactor = self.incByPaving + self.pavingFactor;
      end

      if(not UCsNeighborhood:isEmpty()) then
        UCsNeighborhood:first();
        local UC = UCsNeighborhood:getNeighbor();

        if(UC.ano_criacao < self.timeM) then
          self.UCFactor = self.UCFactor - self.attenFactUCs[UC.hierarquia];
        end

      end

      local placeWeight, place = isInBufferPlaces(cell,
        self.names.buffPlaces, self.names.places, self.trajs.places);

      if( placeWeight ~= nil ) then
        self.infPlaces = self.infPlaces + ((1 + placeWeight) *
          self.infOfPlaces[place.tipo]);
      end

      if(not TIsNeighborhood:isEmpty()) then
        TIsNeighborhood:first();
        local TI = TIsNeighborhood:getNeighbor();
```

```

    self.TIFactor = self.TIFactor - self.attenFactUCs[TI.hierarquia];
end

if(not PAsNeighborhood:isEmpty()) then
    PAsNeighborhood:first();
    local PA = PAsNeighborhood:getNeighbor();

    if(PA.ano_criacao < self.timeM) then
        self.PAFactor = self.PAFactor + self.amplFactPAs;
    end

end

local airstripWeight, airstrip = isInBufferAirstrips(cell,
    self.names.buffAirstrips, self.names.airstrips,
    self.trajs.airstrips);

if( airstripWeight ~= nil ) then
    self.airstripFactor = self.airstripFactor + ((1 +
        airstripWeight) * self.inflAirstrips);
end

local bufferSize = self.pavingFactor * self.secondaryFactor *
    self.UCFactor * self.infPlaces * self.TIFactor *
    self.PAFactor * self.airstripFactor *
    (self.distances[road.level]);

cell.infFactRoad = self.pavingFactor * self.secondaryFactor *
    self.UCFactor * self.infPlaces * self.TIFactor *
    self.PAFactor * self.airstripFactor;

if(distance <= bufferSize and road.anoCriacao <= self.timeM and
    road.status == "active") then
    return true;
else
    return false;
end
else
    return false;
end
end,

weight = function(self, cell, neigh)
    local neighborhood = cell:getNeighborhood(self.names.dist);

    local distance = neighborhood:getNeighWeight(neigh)/1000; -- Converts
                                                                -- from meters
                                                                -- to km

    return self.pavingFactor * self.secondaryFactor * self.UCFactor *
        self.infPlaces * self.TIFactor * self.PAFactor *
        self.airstripFactor * (1/(distance*distance));
end
}

-- Constructor for the neighborhood law of the buffer around the roads
function BuffRoadsLaw( buffRoadsLaw )
    buffRoadsLaw.pavingFactor = 1;
    buffRoadsLaw.secondaryFactor = 1;
    buffRoadsLaw.UCFactor = 1;

```

```

buffRoadsLaw.infPlaces = 1;
buffRoadsLaw.TIFactor = 1;
buffRoadsLaw.PAFactor = 1;
buffRoadsLaw.airstripFactor = 1;

if( buffRoadsLaw.timeM == nil ) then
    error("Neighborhood law cannot be created. Field 'timeM' not
found!");
end;

if( buffRoadsLaw.distances == nil ) then
    error("Neighborhood law cannot be created. Field 'distances' not
found!");
end;

if( buffRoadsLaw.names == nil ) then
    error("Neighborhood law cannot be created. Field 'names' not
found!");
end;

if( buffRoadsLaw.attenFactUCs == nil ) then
    error("Neighborhood law cannot be created. Field 'attenFactUCs' not
found!");
end;

if( buffRoadsLaw.incByPaving == nil ) then
    error("Neighborhood law cannot be created. Field 'incByPaving' not
found!");
end;

if( buffRoadsLaw.infOfPlaces == nil ) then
    error("Neighborhood law cannot be created. Field 'infOfPlaces' not
found!");
end;

if( buffRoadsLaw.amplFactPAs == nil ) then
    error("Neighborhood law cannot be created. Field 'amplFactPAs' not
found!");
end;

if( buffRoadsLaw.inflAirstrips == nil ) then
    error("Neighborhood law cannot be created. Field 'inflAirstrips' not
found!");
end;

if( buffRoadsLaw.trajs == nil ) then
    error("Neighborhood law cannot be created. Field 'trajs' not
found!");
end;

if( buffRoadsLaw.model == nil ) then
    error("Neighborhood law cannot be created. Field 'model' not
found!");
end;

local metatable = {__index = BuffRoadsLaw_};
setmetatable(buffRoadsLaw, metatable);

return buffRoadsLaw;
end

```

## Code 2 – Neighborhood Law of the buffer around places

```
-- Metatable for the neighborhood law of the buffer around the places
BuffPlacesLaw_ = {
  filter = function(self, cell, neigh)
    local neighPlaces = cell:getNeighborhood(self.names.places);
    local neighDistance = cell:getNeighborhood(self.names.dist);

    if((not neighPlaces:isEmpty()) and
      (neighDistance:isNeighbor(neigh))) then

      local distance = neighDistance:getNeighWeight(neigh);
      neighPlaces:first();
      local place = neighPlaces:getNeighbor();

      local bufferSize = self.distBuffer[place.tip];

      if( distance <= bufferSize ) then
        return true;
      end
      else
        return false;
      end
    end,

  weight = function(self, cell, neigh)
    local neighborhood = cell:getNeighborhood(self.names.dist);
    local distance = neighborhood:getNeighWeight(neigh)/1000;
    return 1/(distance*distance);
  end
}

-- Constructor for the neighborhood law of the buffer around the places
function BuffPlacesLaw( buffPlacesLaw )
  if(buffPlacesLaw.names == nil) then
    error("Neighborhood law cannot be created. Field 'names' not found!")
  end;

  if(buffPlacesLaw.distBuffer == nil) then
    error("Neighborhood law cannot be created. Field 'distBuffer' not
found!")
  end;

  local metatable = {__index = BuffPlacesLaw_};
  setmetatable(buffPlacesLaw, metatable);

  return buffPlacesLaw;
end
```

## Code 3 – Neighborhood Law of the buffer around airstrips

```
-- Metatable for the neighborhood law of the buffer around the airstrips
BuffAirstripsLaw_ = {
  filter = function(self, cell, neigh)
    local neighAirstrips = cell:getNeighborhood(self.names.airstrips);
    local neighDistance = cell:getNeighborhood(self.names.dist);
    local UCsNeighborhood = cell:getNeighborhood(self.names.UCs);
    local TIsNeighborhood = cell:getNeighborhood(self.names.TIs);
    local PAsNeighborhood = cell:getNeighborhood(self.names.PAs);
```

```

if((not neighAirstrips:isEmpty()) and
    (neighDistance:isNeighbor(neigh))) then

    distance = neighDistance:getNeighWeight(neigh);
    neighAirstrips:first();
    local airstrip = neighAirstrips:getNeighbor();

    self.UCFactor = 1;
    self.infPlaces = 1;
    self.TIFactor = 1;
    self.PAFactor = 1;

    if(not UCsNeighborhood:isEmpty()) then
        UCsNeighborhood:first();
        local UC = UCsNeighborhood:getNeighbor();
        if(UC.ano_criacao < self.timeM) then
            self.UCFactor = self.UCFactor -
                self.attenFactorUCs[UC.hierarquia];
        end
    end

    local placeWeight, place = isInBufferPlaces(cell,
        self.names.buffPlaces, self.names.places,
        self.trajs.places);

    if( placeWeight ~= nil ) then
        self.infPlaces = self.infPlaces + ((1 + placeWeight) *
            self.infofPlaces[place.tipo]);
    end

    if(not TIsNeighborhood:isEmpty()) then
        TIsNeighborhood:first();
        local TI = TIsNeighborhood:getNeighbor();
        self.TIFactor = self.TIFactor - self.attenFactorUCs[TI.hierarquia];
    end

    if(not PAsNeighborhood:isEmpty()) then
        PAsNeighborhood:first();
        local PA = PAsNeighborhood:getNeighbor();
        if(PA.ano_criacao < self.timeM) then
            self.PAFactor = self.PAFactor + self.amplFactPAs;
        end
    end

    local bufferSize = self.UCFactor * self.infPlaces * self.TIFactor *
        self.PAFactor * self.distBuffer;

    if((airstrip.status == "enabled") and
        (distance <= self.distBuffer)) then
        return true;
    end
    else
        return false;
    end
end,

weight = function(self, cell, neigh)
    local neighborhood = cell:getNeighborhood(self.names.dist);
    local distance = neighborhood:getNeighWeight(neigh)/1000;

    return self.UCFactor * self.infPlaces * self.TIFactor *

```



```

        self.PAFactor * (1/(distance*distance));

    end
}

-- Constructor for the neighborhood law of the buffer around the
-- airstrips
function BuffAirstripsLaw( buffAirstripsLaw )
    buffAirstripsLaw.UCFactor = 1;
    buffAirstripsLaw.infPlaces = 1;
    buffAirstripsLaw.TIFactor = 1;
    buffAirstripsLaw.PAFactor = 1;

    if( buffAirstripsLaw.timeM == nil ) then
        error("Neighborhood law cannot be created. Field 'timeM' not
found!");
    end;

    if( buffAirstripsLaw.names == nil ) then
        error("Neighborhood law cannot be created. Field 'names' not
found!");
    end;

    if( buffAirstripsLaw.attenFactorUCs == nil) then
        error("Neighborhood law cannot be created. Field 'attenFactorUCs' not
found!");
    end;

    if( buffAirstripsLaw.trajs == nil) then
        error("Neighborhood law cannot be created. Field 'trajs' not
found!");
    end;

    if( buffAirstripsLaw.infOfPlaces == nil) then
        error("Neighborhood law cannot be created. Field 'infOfPlaces' not
found!");
    end;

    if( buffAirstripsLaw.amplFactPAs == nil) then
        error("Neighborhood law cannot be created. Field 'amplFactPAs' not
found!");
    end;

    if( buffAirstripsLaw.distBuffer == nil) then
        error("Neighborhood law cannot be created. Field 'distBuffer' not
found!");
    end;

    local metatable = {__index = BuffAirstripsLaw_};
    setmetatable(buffAirstripsLaw, metatable);

    return buffAirstripsLaw;
end

```

#### Code 4 – Neighborhood Law of the buffer around rivers

```

-- Metatable for the neighborhood law of the buffer around the rivers
BuffRiversLaw_ = {
    filter = function(self, cell, neigh)
        local distNeighborhood = cell:getNeighborhood(self.names.dist);

```

```

local riversANANeighborhood =
    cell:getNeighborhood(self.names.riversANA);

local riversPRODESNeighborhood =
    cell:getNeighborhood(self.names.riversPRODES);

local buffRoadsNeighborhood =
    cell:getNeighborhood(self.names.buffRoads);

local UCsNeighborhood = cell:getNeighborhood(self.names.UCs);
local TIsNeighborhood = cell:getNeighborhood(self.names.TIs);
local PAsNeighborhood = cell:getNeighborhood(self.names.PAs);

if((not riversANANeighborhood:isEmpty()) or
    (not riversPRODESNeighborhood:isEmpty())) and
    (distNeighborhood:isNeighbor(neigh)) then

    local airstripWeight, airstrip = isInBufferAirstrips(cell,
        self.names.buffAirstrips, self.names.airstrips,
        self.trajs.airstrips);

    local placeWeight, place = isInBufferPlaces(cell,
        self.names.buffPlaces, self.names.places, self.trajs.places);

    if((not buffRoadsNeighborhood:isEmpty()) or (placeWeight ~= nil) or
        (airstripWeight ~= nil)) then

        local distance = distNeighborhood:getNeighWeight(neigh);
        local river = nil;

        if(not riversANANeighborhood:isEmpty()) then
            riversANANeighborhood:first();
            river = riversANANeighborhood:getNeighbor();
        else
            riversPRODESNeighborhood:first();
            river = riversPRODESNeighborhood:getNeighbor();
        end

        self.UCfactor = 1;
        self.infPlaces = 1;
        self.TIFactor = 1;
        self.PAFactor = 1;
        self.airstripFactor = 1;

        if(not UCsNeighborhood:isEmpty()) then
            UCsNeighborhood:first();
            local UC = UCsNeighborhood:getNeighbor();

            if(UC.ano_criacao < self.timeM) then
                self.UCfactor = self.UCfactor -
                    self.attenFactUCs[UC.hierarquia];
            end

        end

        if( placeWeight ~= nil ) then
            self.infPlaces = self.infPlaces + ((1 + placeWeight) *
                self.infOfPlaces[place.tipo]);
        end

        if( airstripWeight ~= nil ) then

```

```

        self.airstripFactor = self.airstripFactor + ((1 +
            airstripWeight) * self.inflAirstrips);
    end

    if(not TIsNeighborhood:isEmpty()) then
        TIsNeighborhood:first();
        local TI = TIsNeighborhood:getNeighbor();
        self.TIFactor = self.TIFactor -
            self.attenFactUCs[TI.hierarquia];
    end

    if(not PAsNeighborhood:isEmpty()) then
        PAsNeighborhood:first();
        local PA = PAsNeighborhood:getNeighbor();

        if(PA.ano_criacao < self.timeM) then
            self.PAFactor = self.PAFactor + self.amplFactPAs;
        end
    end

    local buffSize = self.UCFactor * self.infPlaces *
        self.airstripFactor * self.TIFactor *
        self.PAFactor * self.distances[river.level];

    cell.infFactRiver = self.UCFactor * self.infPlaces *
        self.airstripFactor * self.TIFactor *
        self.PAFactor;

    if(distance <= buffSize) then
        return true;
    else
        return false;
    end

end

else
    return false;
end
end,

weight = function(self, cell, neigh)
    local neighborhood = cell:getNeighborhood(self.names.dist);
    local distance = neighborhood:getNeighWeight(neigh);

    return self.UCFactor * self.infPlaces * self.airstripFactor *
        self.TIFactor * self.PAFactor * (1/(distance*distance));
end
}

function BuffRiversLaw(buffRiversLaw)
    buffRiversLaw.UCFactor = 1;
    buffRiversLaw.infPlaces = 1;
    buffRiversLaw.TIFactor = 1;
    buffRiversLaw.PAFactor = 1;
    buffRiversLaw.airstripFactor = 1;

    if(buffRiversLaw.timeM == nil) then
        error("Neighborhood law cannot be created. Field 'timeM' not
found!");
    end
end

```

```

end

if(buffRiversLaw.names == nil) then
  error("Neighborhood law cannot be created. Field 'names' not
found!");
end

if(buffRiversLaw.distances == nil) then
  error("Neighborhood law cannot be created. Field 'distances' not
found!");
end

if(buffRiversLaw.trajs == nil) then
  error("Neighborhood law cannot be created. Field 'trajs' not
found!");
end

if(buffRiversLaw.infofPlaces == nil ) then
  error("Neighborhood law cannot be created. Field 'infofPlaces' not
found!");
end

if(buffRiversLaw.inflAirstrips == nil) then
  error("Neighborhood law cannot be created. Field 'inflAirstrips' not
found!");
end

if(buffRiversLaw.attenFactUCs == nil) then
  error("Neighborhood law cannot be created. Field 'attenFactUCs' not
found!");
end;

if(buffRiversLaw.amplFactPAs == nil) then
  error("Neighborhood law cannot be created. Field 'amplFactPAs' not
found!");
end;

if(buffRiversLaw.model == nil) then
  error("Neighborhood law cannot be created. Field 'model' not
found!");
end;

local metatable = {__index = BuffRiversLaw_};
setmetatable(buffRiversLaw, metatable);

return buffRiversLaw;
end

```

### Code 5 – Reconfiguring the buffer around roads.

```

function updateBufferRoads(cellSpaces, neighLaws, timeM)
  print("\tReconfiguring buffer around the roads...");

  neighLaws.buffRoads.timeM = timeM;

  forEachCell(
    neighLaws.buffRoads.trajs.roads,
    function(cell)
      local buffRoadNeighborhood = cell:getNeighborhood(
        neighLaws.buffRoads.names.buffRoads);
    end
  )
end

```

```

function filterBufferRoads(neigh)
    return neighLaws.buffRoads:filter(cell, neigh);
end

function weightsBufferRoads(neigh)
    return neighLaws.buffRoads:weight(cell, neigh);
end

    buffRoadNeighborhood:reconfigure(cellSpaces.csCells,
                                    filterBufferRoads, weightsBufferRoads);
end
);
end

```

### Code 6 – Reconfiguring the buffer around airstrips.

```

function updateBufferRoads(cellSpaces, neighLaws, timeM)
    print("\\tReconfiguring buffer around the roads...");

    neighLaws.buffRoads.timeM = timeM;

    forEachCell(
        neighLaws.buffRoads.trajs.roads,
        function(cell)
            local buffRoadNeighborhood = cell:getNeighborhood(
                neighLaws.buffRoads.names.buffRoads);

            function filterBufferRoads(neigh)
                return neighLaws.buffRoads:filter(cell, neigh);
            end

            function weightsBufferRoads(neigh)
                return neighLaws.buffRoads:weight(cell, neigh);
            end

            buffRoadNeighborhood:reconfigure(cellSpaces.csCells,
                filterBufferRoads, weightsBufferRoads);
        end
    );
end

```

### Code 7 – Reconfiguring the buffer around rivers.

```

function updateBufferRivers(cellSpaces, neighLaws, timeM)
    print("\\tReconfiguring buffer around the rivers...");

    neighLaws.buffRivers.timeM = timeM;

    forEachCell(
        neighLaws.buffRivers.trajs.rivers,
        function(cell)
            local buffRiversNeigh = cell:getNeighborhood(
                neighLaws.buffRivers.names.buffRivers);

            function filterBufferRivers(neigh)
                return neighLaws.buffRivers:filter(cell, neigh);
            end

            function weightsBufferRivers(neigh)

```

```
    return neighLaws.buffRivers:weight(cell, neigh);
end

    buffRiversNeigh:reconfigure(cellSpaces.csCells, filterBufferRivers,
                                weightsBufferRivers);
end
);
end
```