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Coupling cellular automata and Markov chains to design prospective scenarios of urbanization. An application to Strasbourg cross-border area

J.P. Antoni¹, V. Judge^{1,2}, H. Omrani², O. Klein²

¹ThéMA UMR 6049 Université de Bourgogne 6 Boulevard Gabriel 21000 Dijon FRANCE
Email: jean-philippe.antoni@u-bourgogne.fr

²LISER 11 Porte des Sciences L-4363 Esch-sur-Alzette LUXEMBOURG
Email: valentine.judge@u-bourgogne.fr, ichem.omrani@liser.lu, olivier.klein@liser.lu

1. Introduction

In the current context of urbanization, urban sprawl and space consumption have become crucial problems to reach a sustainable territorial development. They cannot be correctly analyzed and managed because they rely on several fields and concern different actors. Indeed, traditional planning approaches and methods are often insufficient to tackle the whole process and anticipate its spatial implications. This context demands to consider spatial planning through more collaborative solutions integrating dynamic and complex spatial modeling and simulations [1]. LucSim (Land use cellular simulation) is a CA-based operational project developed in this context. It offers cartographic and mathematical solutions for harmonizing and sharing spatial data and simulations among scientists, territorial or administrative technicians or elected representatives. In this context, we focus on the Strasbourg-Kehl Area (SKA) experiencing particular growth dynamics and cross-border spatial planning issues.

2. Study area and dataset

The SKA case study takes place on a cross-border field located on the bank of the upper Rhine overlapping a part of South-East Germany and a part of North-East of France. European Corine Land Cover (CLC) database [2] is then used for the analysis of land use change and the measure of soil artificialization. For this research, the original CLC classification was reduced in 9 main classes, focusing mainly on artificial occupations related to human activities (figure 1) for two dates: 1990 and 2006. In the cellular space obtained [3,4] each date corresponds to a system defined by 100 meters grid cells. Cells are associated to one land use category and only one. On the whole case study, the quantitative analysis of the cells evolution allows calculating that urbanized cells expanded by 5.9% considering the overall area between 1990-2006, while natural and agricultural soils decreased by 1.5%. These evolutions can also be summarized for each date within vectors indicating the proportion of each land use category.

3. Methodology

3.1. LucSim CA

Methodologically, we use a Cellular Automata named LucSim, developed from scratch in ThéMA. LucSim is defined as a constrained CA model applied to decision making in urban and land planning. Its main originality (compared to similar geographical CA) is to assume a simplification of the land-use evolution processes into two “fundamental” questions, associated to models able to constraint cellular simulations [5]. The first question “How many?” (how many cells will be concerned by urban sprawl in the future?) is based on Markov chains to define each land-use evolution probability. The second question “What?” (what is the land use category of the cells quantified in the previous step) is directly answered by CA transition rules.









Reclassification (9 Items)		CLC Classification (44 items)	
Name	Color	Code	
Urban Fabric		UR	Continuous urban fabric; Discontinuous urban fabric
Industrial		IN	Industrial or commercial units; Mineral extraction sites; Dump sites; Construction sites
Transport		TR	Road and rail networks and associated land; Port areas; Airports
Equipment		EQ	Green urban areas; Sport and leisure facilities
Agricultural		AG	Non-irrigated arable land; Permanently irrigated land; Rice fields; Pastures; Annual crops associated with permanent crops; Complex cultivation patterns; Land principally occupied by agriculture; Agro-forestry areas
Vine		VI	Vineyards; Fruit trees and berry plantations; Olive groves
Forest		FO	Broad-leaved forest; Coniferous forest; Mixed forest; Natural grasslands; Moors and heathland; Sclerophyllous vegetation; Transitional woodland-shrub
Water		WA	Inland marshes; Peat bogs; Salt marshes; Salines; Intertidal flats; Water courses; Water bodies; Coastal lagoons; Estuaries; Sea and ocean
Natural areas (N/A in SKA)			Beaches, dunes, sands; Bare rocks; Sparsely vegetated areas; Burnt areas; Glaciers and perpetual snow

Figure 1. Land use reclassification from CLC database.

3.2. How many?: Cells quantification

By confronting land use date to date and cell by cell, it is possible to determine cellular changes between 1990 and 2006 and to capture the land use dynamics. These dynamics are therefore presented as a series of possible transitions from one land use category k at time t to a land use category l at $t+\Delta$. It allows building a contingency matrix indicating the number of cells transitions from a category k to a category l . This matrix provides all the elements needed for the construction of a Markov chain [6,7]. We then consider the Markov chain as follows, where Δ represents the transition for a given cell N_i :

$$N_i(t+1) = \sum_{k=1}^m p_{kl} \cdot N_k(t)$$

where $p_{kl} = \frac{\Delta N_{kl}}{N_k(t)} = \frac{\Delta N_{kl}}{\sum_l \Delta N_{kl}}$ and $\sum_l p_{kl} = 1$

	UR	IN	TR	EQ	FI	VI	FO	WA	Σ
2022 (cells)	47,027	13,700	2,640	2,411	235,334	22,735	202,162	6,644	532,653
2022 (%)	9.68	2.82	0.54	0.50	48.46	4.68	41.63	1.37	100
2038 (cells)	49,391	15,339	2,648	2,748	231,921	21,948	202,096	6,566	532,657
2038 (%)	10.22	3.17	0.55	0.57	47.99	4.54	41.82	1.36	100

Figure 2. Expected future land use vectors from MC.

The Markov chain process offers the opportunity to prospectively calculate the future states from the known past states, based on observation of past trends and probabilities. In SKA, LucSim is used to calculate the number of cells in each land use category in 2022, 2038, 2054 (etc.) from 1990 and 2006 land uses (same interval of 16 years between each date). This operation allows representing urban dynamics in the future (figure 2). Figure 2 also indicates that the total number of cells that should be urbanized (including UR, IN and EQ) in 2038 is 8811.

3.3. What?: Changes location

In the second step of the method, CA is constrained with the results of the Markov chain to produce a model for land use change simulations. It means that the CA transition process from a given category to another is automatically stopped when the number of cells given by the MC for each date is reached. This CA transition process corresponds to transition rules, allowing to consider different configurations. By definition [8], CA is based on the assumption that the class of each cell is determined by its neighborhood, that is to say in our case, by the land use categories of surrounding cells within a given radius:

$$\forall i \in E, N_{i,kl} = f(N_{i,k}(t), \%OMEGA_i(t))$$

where

$$\%OMEGA_i = f(N_{k=1}^r, N_{k=2}^r, \dots, N_{k=n}^r) \text{ and } r \in \{0, \dots, \infty\}$$

where E is a set of cells that can undergo a transition (non locked), S_i is the land use of the cell i , N_i is the neighborhood of the cell i within a radius r (at time t), and C_n^r is the number of cells with a land use S within a radius r at time t .

According to observed past transitions, three scenarios are based on the general assumption that new built-up areas can only take place on agricultural fields with contrasted configurations in 2038:

1. “Landscape sprawl” (LS) scenario: residential preferences privilege natural landscapes and rural amenities, but also a relative proximity to slightly dense urban areas (villages).
2. “Urban densification” (UD) scenario: residential preferences privilege dense urban areas, closed to urban amenities (equipment and industry), but relatively far from industry and related nuisances.
3. “Bridge transbording” (BT) scenario: residential preferences privilege mixed residential areas (corresponding both to LS and UD scenarios), but must be located near the crossing points of the border, in rather urbanized areas.

These three scenarios are translated into CA transitions rules. Simulation results are calculated at the original 100 meters resolution of the land use cells but aggregated and mapped within a larger grid of 4000 meters resolution to improve changes visualization (figure 3).

4. Results

LS scenario leads to gain 8976 cells in only 2 iterations. This result can be explained considering spatial configuration that are very generic and numerous in the case of the rules created upon. UD scenario leads to gain 9391 cells in 9 iterations. A much higher number of iterations is needed. The rule set configuration make the transition less likely to happen and to objective from the MC constraint can only be achieved waiting for newly urbanized cells to be taken into account. BT scenario leads to gain 8852 cells in 10 iterations, roughly the same number as Urban Densification scenario. As the previous scenario, few spatial configurations are adapted to the transition toward urban. This situation leads to highly concentrate the urban development in some place of the area, located close to the Rhine river and crossing points (bridges).

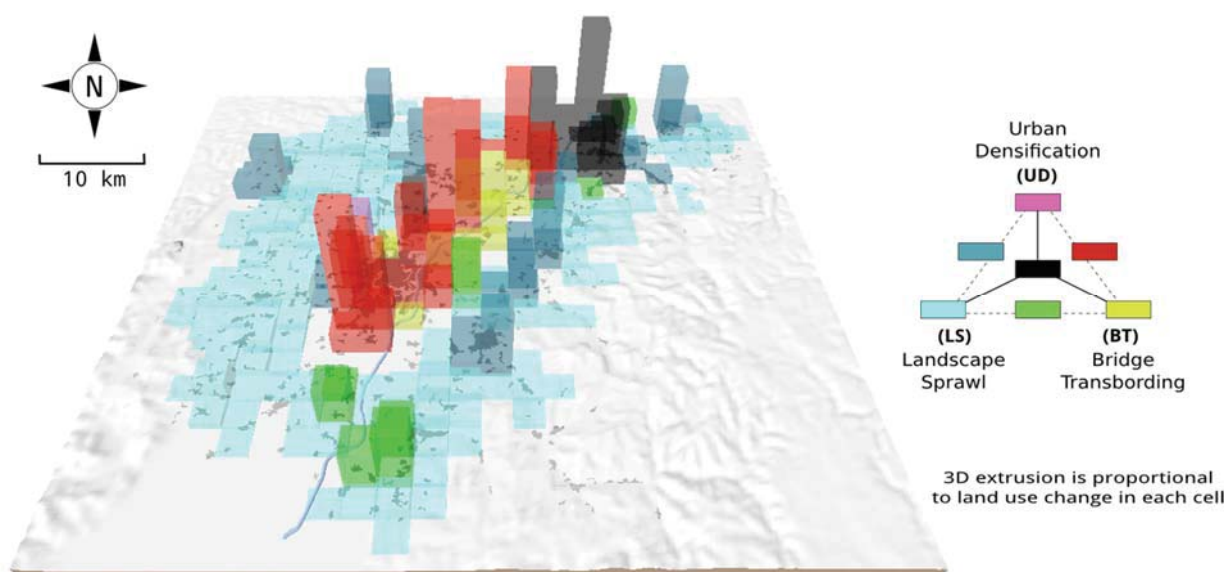


Figure 3. Expected future changes location form CA.

Results also show that this two-steps modeling allows the study of urban changes with efficiency. The composition of the model appears simplified enough to be simultaneously understood by all the actors concerned with urban planning. LucSim then allows decision making for territorial development and innovation, in the perspective of a more sustainable land and urban planning [9].

5. Conclusion

This paper presents an application of the LucSim model on the Strasbourg-Kehl (France-Germany) cross border area, using Corine Land Cover classification. Each cell of the CA is then characterized by its neighborhood (land-use and distances) and transition rules are empirically calibrated by determining and calculating Markov chains and running CA. Three scenarios are developed: (i) a Landscape Sprawl scenario where residential preferences are located around landscape and rural amenities closed to slightly dense urban areas; (ii) a Urban Densification scenario focused on urban residential preferences, closed to urban amenities, but relatively far from nuisances (industry); and finally (iii) a mixed Cross-Border scenario with residential preferences located around the crossing points of the border, in rather urbanized areas. These three scenarios are simulated until 2038 and, although they are not statistically validated, the results are compared and discussed.

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