Using Constraint Cellular Automata to Simulate Urban Development in a Cross-border Area

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Abstract: Urban sprawl and space consumption have become key issues in sustainable territorial development. Traditional planning approaches are often insufficient to anticipate their complex spatial consequences, especially in cross-border areas. Such complexity requires the use of dynamic spatial simulations and the development of adapted tools like LucSim, a CA-based tool offering solutions for sharing spatial data and simulations among scientists, technicians and stakeholders. Methodologically, this tool allows us to simulate future land use change by first quantifying and then locating the changes. Quantification is based on Markov chains and location on transition rules. The proposed approach is implemented on the Strasbourg-Kehl cross-border area and calibrated with three contrasting prospective scenarios to try to predict cross-border territorial development.

1 CONTEXT AND RESEARCH OBJECTIVES

In the current context of increasing urbanization and daily mobility, urban sprawl and space consumption have become crucial issues for achieving sustainable territorial development (European Environment Agency 2006). This problem is further complicated in the case of cross-border areas where operational procedures on each side of the frontier differ from an administrative, legal and cultural point of view. Moreover, open border areas are currently undergoing particular growth dynamics which have given rise to numerous cross-border spatial planning issues. In this context, the Strasbourg-Ortenau Eurodistrict Project (French-German cross-border territory) is promoting the development of cross-border initiatives in what is a pilot scheme for the EU. Within this pilot region, we will be focusing specifically on the Strasbourg-Kehl cross-border Area (SKA).

Trans-national territorial analyses are constrained by the problem of geographical information and data harmonization (i.e. scale, temporality, accuracy of data). Classical planning approaches and methods are therefore often incapable of addressing the complexity of these situations and predicting their spatial implications. In this context, spatial simulations are widely viewed as an appropriate tool to help planner stake decisions. Such simulations rely on several kinds of simulations models, among which Cellular Automata (CA) are particularly well designed for managing spatial planning issues.

CA are considered useful tools for modeling and simulating urban development because they allow us to implement simple spatial rules based on empirical knowledge that take into account the role of neighborhood in urban growth processes. They have been widely used to simulate land use changes and scenarios for future urban development in different contexts. The seminal work of Couclelis (1985, 1987), White and Engelen (1993), Batty and Xie (1994) and later Clarke et al. (1997) paved the way for CA to be considered a powerful tool for modeling and simulating spatial phenomena of various types. The research on CA gathered new momentum during the 2000s in a surge in research that coincided with a second wave of faster and cheaper computational capacities (Torrens 2000, Benenson and Torrens 2004, Couclelis 2005, Koomen et al. 2011). The aim of this paper is to present prospective urban development scenarios for the Strasbourg-Kehl area in the medium term.

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2 METHODOLOGY

From a methodological point of view, the LucSim CA model can be defined as a constrained cellular automata designed to aid decision-making in urban and land planning. Its main original feature (compared to similar geographical CA) is to simplify the land-use evolution processes into two "fundamental" steps, namely the quantification and location of future land use changes. Land use is assessed within a cellular grid space obtained from the European Corine Land Cover classification.

2.1 Quantification of Land Use Changes

Our first step was to quantify the land use change process. Comparing two static land use images or vectors (1990, 2006) is of little interest in the context of a dynamic simulation, but finding out what happens between each image can enable us to formulate a transition process. By comparing the land use categories date by date and cell by cell, it is possible to determine cellular changes between t and t+1, and identify the land use dynamics. Theoretically, each cell can move from one land use category to another, or remain in the same category. The dynamics of the model can therefore be presented as a series of possible transitions from one land use category k at time t to another land use category l at t+1.

The Markov chain process gives us the chance to prospectively calculate future states from known past states, based on observation of past trends and probabilities. According to the method, this calculation is based on the assumption that future changes will follow the trend of past changes, but as it is based on a matrix calculation, this trend is not necessarily linear. In our case, LucSim uses the original transition matrix 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 system gives us a better picture of urban dynamics by calculating land use vectors for each future date. It also indicates that the total number of cells that should be urbanized (including UR, IN and EQ categories) by 2038 is 8,811.

2.2 Location of Land Use Changes

The second step was to try to identify the location of land use changes with a method based on Cellular Automata. Cellular Automata have the double advantage of being able to determine the land use category of cells according to their neighbourhood, and also to integrate the previous Markovian process. By definition, CA are based on the assumption that the class of each cell is determined by its neighbourhood, or in our case, by the land use categories of surrounding cells within a given radius.

CA can then be constrained with the results of the Markov chain to produce a model for land use change simulations. This means that the CA transition process from one given category to another is automatically halted when the number of cells given by the MC for each date is reached. This CA transition process is based on transition rules that allow us to consider different configurations. The main problem is then to define relevant rules to simulate realistic scenarios of spatial development, a generalized problem in all modelling and especially in model calibration.

3 SPATIAL DEVELOPMENT SCENARIOS

We decided to base all our scenarios on the general assumption that new built-up areas can only be developed on agricultural fields. These scenarios present three contrasted configurations for land use changes in 2038: urban sprawl, urban densification and cross-border development based on the bridge connections available on the SKA specific test-field. Although results are calculated at the original 100 meters resolution of the land use cells, they are aggregated and mapped within a larger grid with a resolution of 4,000 meters to improve visualization of the changes.

3.1 Landscape Sprawl

The main idea of the "Landscape Sprawl" (LS) scenario is that future residential preferences will favor natural landscapes and rural amenities, as well as relative proximity to slightly dense urban areas (villages).

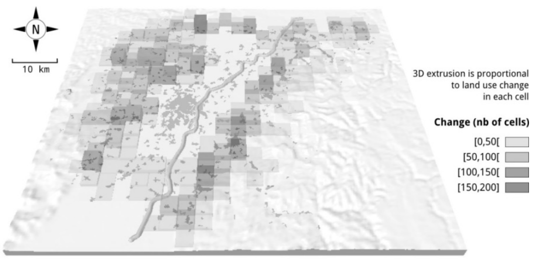

Figure 1: "Landscape sprawl" scenario: land use changes simulation in 2038.

The LS scenario (Fig. 1) leads to a gain of 8,976 cells in only 2 CA iterations. This result can be explained by considering spatial configurations that are very generic and numerous in the case of the rules created above. LucSim therefore quickly spots the cells that meet the requirements to be transformed into urban land. A typical example of this process of urbanization can be seen between the “Piémont” area and the high density urban area of Strasbourg. We can also observe a generalized expansion of areas with low urban density (max 200) and a high dispersion of the cells that become urbanized. Nevertheless, this general dispersion is quite homogeneous except for a slight concentration around small cities. The urban expansion on the German side appears to be more linear than in France, which is probably due to the topographic features in that area.

3.2 Urban Densification

The main idea of the “Urban Densification” (UD) scenario is that future residential preferences will favor dense urban areas, close to urban amenities (e.g. parks, sport and leisure facilities), but relatively far away from industry and related nuisances.

Figure 2: “Urban densification” scenario: land use changes simulation in 2038.

The UD scenario (Fig. 2) produces a gain of 9,391 cells in 9 iterations. A much higher number of iterations is needed because the rules for this configuration make the transition less likely to happen. Moreover the Markov constraint can only be achieved when newly urbanized cells are taken into account. This explains why the process is slower and more iterations are required to converge toward the solution provided by the set of rules for the UD scenario. In this case new urbanization is concentrated around the bigger cities and expands on the existing urban structure rather than following the area’s physical geography features. The fact that the existing urban area is already much larger on the French side favors further urbanization on this side. The urban density is clearly higher than in the LS scenario (max 408).

3.3 Bridge Transbordering

The main idea of the “Bridge Transbordering” (BT) scenario is that future residential preferences will favor mixed residential areas (with both LS and UD scenarios), located in quite heavily urbanized areas near the border crossing points.

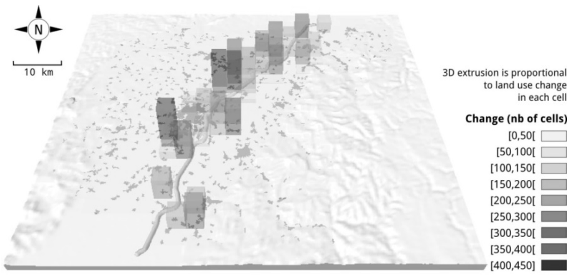

Figure 3: ‘Bridge Transbordering’ scenarios: simulation of land use changes in 2038.

The BT scenario (Fig. 3) leads to gains of 8,852 cells in 10 iterations, roughly the same number as the UD scenario. As in the previous scenario, few spatial configurations are adapted to the transition towards urban land use categories. This situation leads to urban development being highly concentrated in certain places in the study area (max 450), most of which are close to the River Rhine and its crossing points (bridges, ferry). New high density urban development is also predicted around the big cities. Urban development will be essentially linear and more intensive on the French side (especially around the southern part of Strasbourg city, and close to the Gambsheim dam). The three places most affected in the German part are: Lahr, Kehl and around Baden-Baden.

4 DISCUSSION

The three residential development scenarios presented above in succinct form were developed on the basis of expert judgement. From a scientific point of view, our results have not been validated. Forecasting the future in a complex context is difficult and in the absence of a crystal ball, there is no known technique for validating future urban development results at such a fine scale. Nevertheless the various scenarios involve realistic processes and rules based on accurate expert knowledge to provide images of the future that can be used in debate and decision-making about desirable urban development and land-use changes. In this context, the objective of the model is not to separate France from Germany by offering independent analyses or forecasts for each one, but to reflect on scenarios for their common future development.

5 CONCLUSION

By comparing these different scenarios, we can see that this model can assess the impact of single neighbourhood rules on urban development. This global modelling enables us to study urban changes easily and efficiently. Breaking down the process into two steps (MC+CA) makes it sufficiently straightforward to be simultaneously understood by all the stakeholders involved in urban planning. LucSim therefore allows a wide range of different points of view to be considered and specific actions to be imagined for territorial development and innovation, within the perspective of more sustainable land and urban planning.

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