Chapter 14
Constraint Cellular Automata for Urban Development Simulation: An Application to the Strasbourg-Kehl Cross-Border Area

J.P. Antoni, V. Judge, G. Vuidel and O. Klein

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.

Keywords Cellular automata · Markov chains · Cross-border area · Land use scenarios · Prospective

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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 (Stoklosa and Besier 2014). Moreover, open border areas are currently undergoing particular growth dynamics which have given rise to numerous cross-border spatial planning issues (Coplan 2012; Kaiser 2012; Kolossov 2012). 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. This project is currently supported by local political actions (Antoni 2009) and is widely backed by the European Union. Within this pilot region, we will be focusing specifically on the Strasbourg-Kehl cross-border Area (SKA). SKA is located on the banks of the upper Rhine and covers parts of South-West Germany and North-East France. The area is physically composed of a large plain that is symmetrically organized and delimited by the Vosges and the Black Forest mountains (*graben*). The River Rhine is not only a major fluvial axis running through the middle of the region, but also forms the border between France and Germany, which are linked by bridges with high levels of traffic (Durr and Kayali 2014). Despite its geomorphological consistency, SKA has two different geographic configurations (Fig. 2). The French side is currently highly urbanized around the agglomeration of Strasbourg, while the German part remains predominantly rural. Despite this, people on both sides of the border suffer similar residential housing issues such as urban sprawl, air pollution and congestion. SKA is an interesting case to study for three main reasons that make it quite unique. Firstly, because there is no strong cross-border differential like that between France and Luxembourg or between France and Switzerland (job market, taxes). Secondly, because there is a genuine political will to create a Eurodistrict (defined by the UE as a cross-border administrative and planning institution) and finally because residential mobility from Strasbourg to Kehl and from Germany to France (northern part of the case study) is becoming more and more important.

Nevertheless, despite the cooperation at local and European level, cross-border planning issues remain difficult to manage because many different disciplines (e.g. urban planning, transport, housing, labour market, industrial and commercial investment etc.) and stakeholders are involved. Moreover, 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. This means that spatial planning must look for more collaborative solutions that integrate dynamic and complex spatial analyses in a prospective way. Any strategy to implement sustainability and planning with the available regulatory tools requires planners to imagine the future layout of their territory. Predictions of this kind are however very difficult to make and numerous experiments have shown that a simple trend projection often provides poor spatial extrapolations, disconnected from territorial realities. 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. The methodology (argued in Sect. 2.2) was used to select the year 2038 as a suitable target date for these predictions. This provides a sufficiently long period of time for prospective anticipation and decision making in the field of land planning and regulation policies. Simulations are provided by LucSim (*Land Use Change Simulation*), an open-source operational CA dedicated to geographical analysis and simulations (Antoni 2006). This CA has been developed *from scratch* to offer comprehensive and user-friendly cartographic and mathematical solutions, but also to harmonize and share spatial data and simulations among scientists, territorial and administrative technicians, elected representatives and stakeholders. We use it to construct and simulate cross-border scenarios showing how residential growth in border areas can be planned and controlled by means of comprehensive rules and regulations. We begin by presenting the main assumptions of the CA model, based both on the Markov chains process and the creation of transition rules (Sect. 2), before going on to calibrate three contrasted scenarios for predicting future urban changes (Sect. 3). Results are then presented and discussed in the Conclusion (Sect. 4).

2 Methodology

From a methodological point of view, LucSim 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 Data and Material

As the Strasbourg-Kehl case study takes place on a cross-border field, it is essential to use harmonized data. Indeed, to avoid any mismatch problem between data from France and data from Germany, all aspects of the objects being studied must be defined in exactly the same way on both sides of the border at temporal (collection date), spatial (spatial accuracy and resolution) and thematic levels (the different land use categories). The best way to tackle this issue is to use data created at a higher level within the framework of international cooperation. Corine Land Cover (CLC) is a database designed to that effect. It is a European biophysical land occupation database provided by the European Environment Agency at several dates. With a resolution of 100 m, the database classifies land use into 44 items or categories (Fig. 1) and is used above all to analyze land use change and measure the artificialization of land. For the research presented in this chapter, we reduced the land use classification to 8 main categories, focusing mainly on artificial occupation of land for human activities for two dates: 1990 and 2006 (Fig. 2).

In the cellular space obtained from CLC, each date corresponds to a system defined by N cells in a grid. Cells are associated to one, and only one, land use category. The specific land use of any given cell N_i at time t is referred to as k and the land use of any given cell N_i at time $t + 1$ is called l.

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

Fig. 1 Corine land cover reclassification in 8 classes

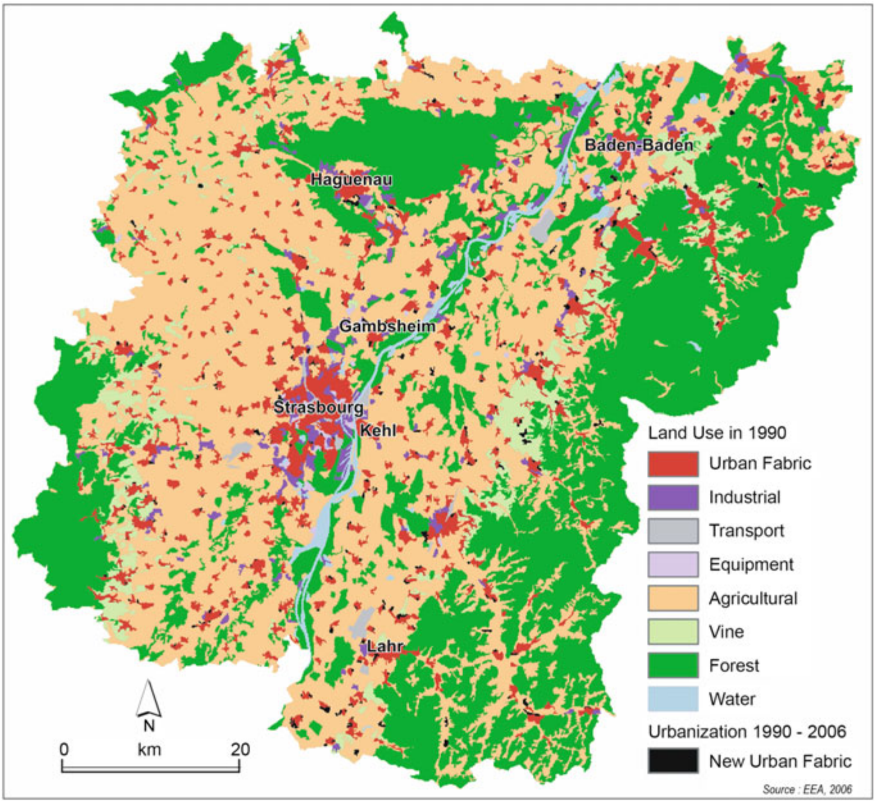

Fig. 2 Land use in the Strasbourg-Kehl area in 1990 and 2006

Table 1 Past land-use vectors

	UR	IN	TR	EQ	FI	VI	FO	WA	∑
1990 (cells)	42,143	10,163	2,628	1,747	242,397	24,410	20,232	6,850	532,659
1990 (%)	8.59	2.07	0.54	0.36	49.42	4.98	41.25	1.40	100
2006 (cells)	44,612	11,977	2,634	2,078	238,826	23,556	202,237	6,739	532,659
2006 (%)	9.14	2.45	0.54	0.43	48.94	4.83	41.44	1.38	100

In the SKA, the quantitative analysis of $N_{i,k}$ and $N_{i,l}$ (1990 and 2006) shows that urbanized cells (UR) expanded by 5.9% between 1990–2006, while natural and agricultural soils (FI) decreased by 1.5%. Land use cover can be summarized more precisely for each date within vectors indicating the proportion of each land use category (Table 1).

2.2 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 $t + 1$. For a given cell N_i, a transition Δ can be written as:

$$\Delta \mathrm{N}_{\mathrm{i,kl}} = 1 \text{ if } N_{\mathrm{i,k}}(t) = 1 \text{ and } N_{\mathrm{i,l}}(\mathrm{t}+1) = 1$$

To simplify the complexity resulting from the high number of cells and possible transitions, changes can be aggregated by land cover categories. The aggregate transition for the complete system is then:

$$\Delta \mathrm{N}_{\mathrm{kl}} = \sum_{\mathrm{i}=1}^{n} \Delta \mathrm{N}_{\mathrm{i,kl}}$$

This formulation allows us to build a contingency matrix indicating the number of cell transitions from a category k to a category l between t and $t + 1$ (i.e. between 1990 and 2006). When associated with the previous vectors, this matrix provides all the elements needed for the construction of a Markov chain (MC). In the literature, a Markov chain is defined as a mathematical process where transition probabilities are conditional on the past, and express the state of a variable at a time t as a function of observations of this variable at $t - 1$ (Feller 1968, Berchtold 1998). It relies on the connection of three items: (i) the description of the relative values associated to an initial state (land occupation visualized as a vector for example); (ii) a transition matrix expressing the transition probabilities of different groups of

Table 2 1990–2006 transition matrix

	UR	IN	TR	EQ	FI	VI	FO	WA	$\sum$
UR	**0.9893**	0.0063	0.0001		0.0038	0.0003		0.0001	1
IN	0.0093	**0.9539**	0.0006	0.0076	0.0120		0.0100	0.0066	1
TR		0.0030	**0.9844**	0.0118	0.0008				1
EQ	0.0074	0.0137		**0.9788**					1
FI	0.0104	0.0069	0.0001	0.0011	**0.9794**	0.0005	0.0010	0.0006	1
VI	0.0106	0.0016			0.0274	**0.9593**	0.0011		1
FO	0.0001	0.0013			0.0018	0.0001	**0.9962**	0.0005	1
WA		0.0028	0.0001		0.0159		0.0441	**0.9371**	1

observations from one category to another; and (iii) a diachronic transformation by an operator in the form of a matrix multiplication iteration.

If we follow this procedure, land use at time $t + 1$ can be simulated by multiplying the corresponding vector at time t by the corresponding contingency matrix, after the transformation of the latter into transition probabilities from a land use category k to another l. To transform observed contingencies into transition probabilities, we use the following:

$$p_{\mathrm{kl}}(t) = \frac{\Delta \mathrm{N_{kl}}}{N_k(t)} \text{ and } \sum_{\mathrm{k}=1}^{m} p_{\mathrm{kl}}(t) = 1$$

We then consider the Markov chain as follows:

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

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

According to this formulation, 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. Moreover, the values of the transition matrix can also be modified by users of the model to integrate different parameters for the quantification of future land use changes. 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, as presented in Table 3.

This table also indicates that the total number of cells that should be urbanized (including UR, IN and EQ categories) by 2038 is:

Table 3 Expected future land-use vectors

	UR	IN	TR	EQ	FI	VI	FO	WA	∑
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

$$\frac{[N_{\mathrm{k=UR}}(\mathrm{t}+1)+\mathrm{N}_{\mathrm{k=IN}}(\mathrm{t}+1)+\mathrm{N}_{\mathrm{k=EQ}}(\mathrm{t}+1)] \\ -[N_{\mathrm{k=UR}}(t)+\mathrm{N}_{\mathrm{k=IN}}(t)+\mathrm{N}_{\mathrm{k=EQ}}(t)]}{8,811}$$

2.3 *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. Developed as a result of the progress of artificial intelligence in computer science, Cellular Automata have the double advantage of being able to determine the land use category of cells according to their neighborhood, 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 neighborhood, or in our case, by the land use categories of surrounding cells within a given radius:

$$\forall i \in \mathrm{E}, \mathrm{V}_{\mathrm{i,kl}} = \mathrm{f}\left(V_{\mathrm{i,k}}(t), \Omega_i(t)\right)$$

where

$$\Omega_i = \mathrm{f}\left(V^r_{\mathrm{k=1}}, \mathrm{V}^r_{\mathrm{k=2}}, \ldots, \mathrm{V}^r_{\mathrm{k=n}}\right) \text{ and } r \in \{0, \ldots, \infty\}$$

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

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 modeling and especially in model calibration.

3 Spatial Development Scenarios

After analyzing past transitions (Table 2), we decided to base all our scenarios on the general assumption that new built-up areas can only be developed on agricultural fields (FI). 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). This means that residential development of new built-up areas is determined by the following transition rules:

- The proportion of UR in a radius of 200 meters must be over 30%.
- The proportion of FI in a radius of 500 meters must be over 50%.
- There must be at least 1 VI cell in a radius of 5 km.
- There must be at least 1 FO cell in a radius of 5 km.
- The total number of new built-up cells is less than 8,811.

The LS scenario (Fig. 3) 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 homogenous 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.

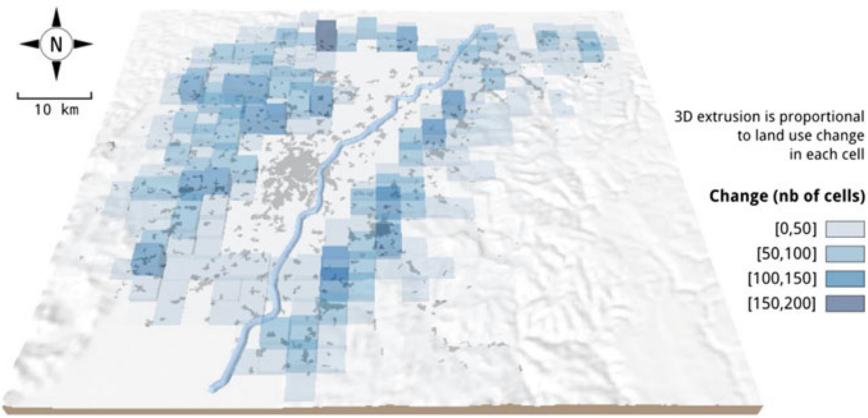

Fig. 3 "Landscape sprawl" scenario: land use changes simulation in 2038

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. Consequently, residential development of new built-up areas will be determined by the following transition rules:

- The proportion of UR in a radius of 200 meters must be over 30%.
- There must be at least 1 EQ cell in a radius of 2 km.
- There must be no IN cells in a radius of 1 km.
- There must be at least 1 IN cell in a radius of 2 km.
- The total number of new built-up cells is less than 8,811.

The UD scenario (Fig. 4) 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).

Fig. 4 "Urban densification" scenario: land use changes simulation in 2038

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. Consequently, residential development of new built-up areas is determined by the following transition rules:

- The proportion of UR in a radius of 200 meters must be over 30%.
- The proportion of FI in a radius of 500 meters must be over 25%.
- There must be at least 1 IN or 1 EQ cell respectively in a radius of 1.5 and 1 km.
- There must be at least one bridge in a radius of 7.5 km.
- The total number of new built-up cells is less than 8,811.

The BT scenario (Fig. 5) 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.

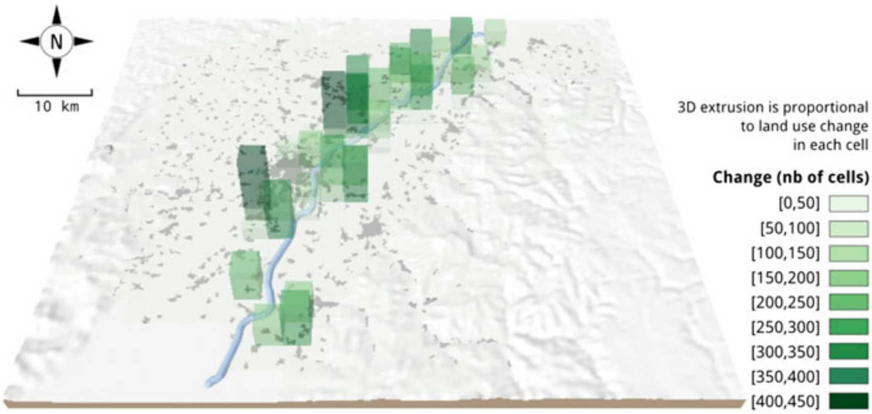

Fig. 5 'Bridge Transbordering' scenarios: simulation of land use changes in 2038

4 Discussion

The three residential development scenarios presented above in succinct form were developed on the basis of expert judgment. Rather than attempting to justify these expert opinions, our aim is to use CA to highlight the compatibility of the language used by experts, decision makers and modelers. To this end the scenarios are expressed verbally and in the form of simple rules that are easy to implement in cellular automata. From a thematic point of view, we have also shown that the scenarios are initially very contrasting and that the resulting CA rules naturally lead to very different configurations in terms of land use changes. However, the results produced by the CA also show some similarities. For example some areas are urbanized whatever the scenario. This convergence clearly shows the areas where the main challenges for future urbanization will lie. It also demonstrates the utility of the tool when taking planning decisions and when debating future regulation policies.

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. The method presents a CA-based tool that, according to its structure and data-feeding, can be widely used on both sides of the border by institutions that aim to merge at some time in the future to form a Euro district. 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.

Another way to construct prospective scenarios and define CA rules could involve using a Decision Tree (Judge et al. 2015) or Artificial Neural Networks (Basse et al. 2014). Artificial intelligence helps to automatically determine transition rules based on the analysis of past processes (e.g. 1990–2000–2016). However, such artificial intelligence based solutions only produce a continuation of past trends. In a move to more sustainable forms of development, this should not necessarily be exclusive and other trends and directions that mix these approaches should be included in the simulations. However, forecasting the future in a complex context remains difficult, even if supported by geographic cellular automata models, or indeed any other intelligent methodology for planning and decision making. Anyway, even if they can provide convincing answers that anticipate land use changes, CA remain totally silent on mobility issues (Timmermans 2003). CA can however be combined with residential mobility models, daily mobility or traffic models to simulate the flows generated by land use changes. In this context, a possible extension of this work could involve coupling different models together to propose a more complex LUTI (Land Use and Transport Integrated) model (Wegener and Fürst 1999), in which a CA approach can make an important contribution.

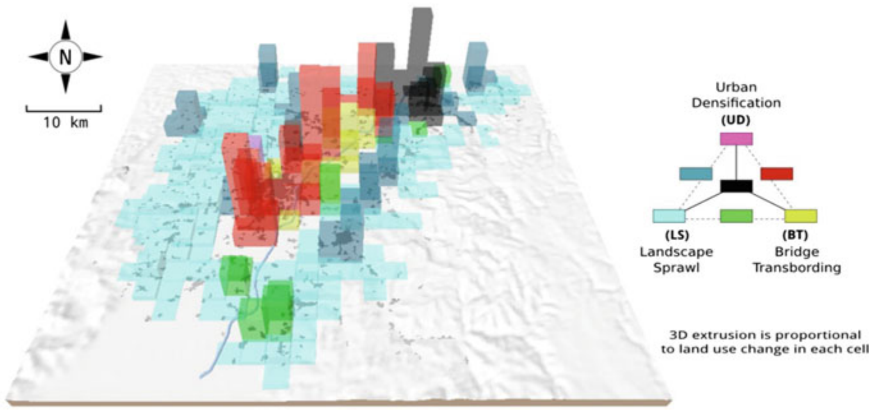

Fig. 6 Land use changes in 2038: combination of the results of the simulated scenarios

5 Conclusion

If we combine the results of the three simulations, areas with differing potential for urbanization emerge. Two specific areas (in black on Fig. 6) systematically appear in all the scenarios; this suggests that these areas have a particularly complex spatial configuration in that they are near the border, close to cities and suburban. Development is therefore likely in these areas irrespective of the preferences associated with each scenario. Some other areas result from the combinations of two of the three scenarios: (i) in green, the "border sprawl", namely a suburbanization along the border but outside the main urban centers; (ii) in red, a densification around the border crossing points in the north of the study area and around Strasbourg; (iii) and finally in blue, a dispersed suburban area away from both large cities and the border area.

By comparing these different scenarios, we can see that this model can assess the impact of single neighborhood rules on urban development. This global modeling 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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