Assessing the Dynamic Land Use Model METRONAMICA on a Local Level

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Abstract

Policy makers are faced with spatial activities and have to decide about future development. Assistance can be found when consulting computer based decision support systems. One example is the dynamic land use model METRONAMICA, based on a cellular automaton as allocation methodology. For this research, METRONAMICA was applied on a study area in the Netherlands. Here major changes and redevelopments are planned but different opinions considering future growth perspectives exist and the model should support the decision making process. The question was however, if it provides accurate results and usable support when being applied at local level (municipality) at a high resolution (cell size 25 × 25 m). For assessing the quality of calibration, two measurements were applied: Kappa statistics and Zipf's law. Special attention was paid to the cell size and the size of the neighbourhood that the cellular automaton takes into consideration (8 cell radius). In order to evaluate the models' possibilities for local planning support, development scenarios were run until the year 2040. The results show that a local application seems to be possible, but more detailed data should be available to model more detailed land use functions. Then, more specific transition rules could be implemented, accounting for dynamics in the urban environment.

1 Introduction

Urban areas can be regarded as information-rich systems, consisting of many abstract interactions and connections. They are one of the most successful creations of human society (WHITE & ENGELEN 1993). Much research has been carried out on surveying and governing urban development. Its complexity resembles chaos or noise, because each type of region in a city interacts with any other type: growth, change, decline and restructuring continuously take place at the same time (WHITE & ENGELEN 1993). When policy maker have to find optimal future development strategies, they can be assisted by computer based decision support systems (DSS). Such DSS in urban areas have for instance been applied in: Santa Barbara, USA (HEROLD et al. 2003), Nanjing, China (SHENG et al. 2008), the Puget Sound region (WADDELL et al. 2002), island la Réunion (LAJOIE & HAGEN-ZANKER 2007) and Vitoria-Gasteiz, Spain (VAN DELDEN et al. 2005).

Land use models are part of such DSS. Their spatial detail represents local features that people in a city experience and planners must deal with (WHITE & ENGELEN 1997).

Advantages of land use models are their interactivity, the visualization, linkage to GIS and the easy incorporation of raster-based spatial data (JANTZ et al. 2004).

A methodological approach for modelling future developments is a cellular automaton (CA) model. It is based on cell transitions: Each cell within a neighbourhood is weighted differently depending on its type of land use. New land uses will change the neighbourhoods' attractiveness for activities already present and others searching for space. CA offer important benefits and assistance when modelling land-use dynamics. BATTY and XIE (1994, 33) illustrated the power of CA on urban simulations. Furthermore, CA are able to simulate different types of urban forms (YEH & LI 2002) and investigate the evolution of urban spatial structure over time (WHITE & ENGELEN 2000). The land use model METRONAMICA makes use of such a CA. It has been applied worldwide to a wide range of cities, regions and countries at a regional level (VAN DELDEN & ENGELEN 2006), (VAN DELDEN et al. 2005), (LAJOIE & HAGEN-ZANKER 2007). In the following study, the usability of METRONAMICA on a local level with a high spatial resolution (cell size 25 × 25 m) is introduced and it is assessed if the model provides accurate results and usable support for planning decisions. Local in this case is defined as "involving or affecting only a restricted part of the organism" (ENCYCLOPÆDIA BRITANNICA 2009), meaning that a particular part of an area is cut out and examined without taking neighbouring areas into consideration. The applied high resolution data visualizes local characteristics and helps to separate different land cover classes from each other, such as urban, peri-urban and industry.

2 Study Area

The municipality Weert is situated in the south of the Netherlands. Its size is about 104 km^2. For the future population shrinkage is expected and ETIL (2008) created a scenario with slow growth until 2021, which is then followed by shrinkage until 2040. Due to increasing prosperity and demand for larger and second homes the use of residential land is expected to grow in the future. The required living space is supplied by the transformation of farm-land and abandoned stables remaining from the zero-grazing sector (KOOMEN & GROEN 2004). Today, agriculture makes up 58 % of the total area (61 km^2). It decreases by supplying space for other functions, e.g. urban areas and nature. Through the study area runs a national expressway, two provincial roads (N280 and N292) and a train station is available. The N280 road currently leads along the business park "Moesdijk". It is supposed to be redirected, leading south and counter steering traffic from the city centre (Provincie Limburg 2007).

Weert is planning a new business park, the Kampershoek-North with two possible perspectives: either a mix of light industry and retail or only modern mixed industry. The final decision depends on developments concerning the Moesdijk business park, consisting at the moment of light industry and retail. The Moesdijk is supposed to be redeveloped either for retail or for industry. Two retail areas are not possible within the municipality. A decision has to be made: will retail move to the Kampershoek-North or to the Moesdijk?

3 Data and Method

METRONAMICA comprises a dynamic land use model applied to the full territory of the area to be modelled. Main feature is its modularity, meaning that METRONAMICA consists several independent blocks. The spatial resolution normally varies between 50 and 1000 m and results are calculated on a yearly basis. The model is based on a land use map and accounts for local constraints, implemented via a zoning, suitability and accessibility map (RIKS bv 2005, 10). The applied model consists of two modelling levels: A global level of the entire modelled area, where main economic activities, demographic growth and natural land use categories are calculated. Furthermore a local level, where single cell-state requirement is calculated. Here, detailed allocation of people and land use is determined.

The allocation on the local level is based on a constrained cellular automaton. The entire modelling area is represented by a mosaic of raster cells, each cell having one known state. All cells are simultaneously evaluated and updated. A set of rules (transition rules), determines whether or not a cell changes when it is evaluated. It depends on the quality of its neighbourhood that consists of a radius of up to 8 cells and also includes the cell itself (maximum of 196 cells) (VAN DELDEN et al. 2005). Cells change to that land use function, for which they have the highest transition potential, until regional demands are satisfied.

There is no programming required to set up an application and a graphical user interface provides access to all variables, parameters and maps. Manual calibration and validation is required, the output is a new land use map for each year and information in the form of charts and animations. In the following, variables and input datasets are introduced that were used to set up the modelling application for Weert (Fig. 1).

(1) *Temporal extent*: modelling is carried out from the year 2004 until 2040 (36 years).
(2) *Spatial extent*: a single layer mode was chosen, taking two modelling levels into consideration. The global level consisting of the municipality Weert and the local level consisting of a constrained CA.
(3) *Resolution*: the cell size used in this application is 25 × 25 m.
(4) *Neighbourhood configuration*: the neighbourhood is based on a radius of 8 cells, including the cell itself (hence, consisting of 196 cells). Based on the cell size of 25 m, is the maximum neighbourhood distance 200 m.
(5) As *land use map*, the Dutch "National Land Cover Database" (Landelijk Grond-gebruiksbestand Nederland) was joined with the "Land Use Base of Statistics Netherlands" (Bestand Bodem Gebruik). The land use map is in raster file format and includes three categories: *land use functions* that are driven by external factors and change actively, v*acant land uses* that are taken over by land use functions if they require more space (e.g. nature), and *land use features* that affect the transition potential of other cells but stay constant during the modelling process (e.g. water, roads). Because only land use *functions* can actively be modelled within METRONAMICA numbers and figures concentrate on these and leave out land use *features* and *vacant* states.
(6) *Zoning maps* impose constraints or *stimulate* trends, based on master plans or other planning material (RIKS bv 2005, 10). They determine which cells are allowed to be taken over by a certain land use function. For the land use functions urban, peri-urban,

industry and retail a zoning map was created. All zoning maps are introduced as ASCII raster files. They contain the values 0, 1, 2 and 3, allowing this way to include also a temporary aspect. On raster cells assigned with a 0 growth is permitted from 2004 on. On cells with the value 1 growth is permitted only from 2008 on, with a value 2 from 2020 on and on cells with a value 3 any growth is prohibited.

(7) *Accessibility* maps allow for the importance and quality of infrastructure elements (road vs. highway) for a particular activity or land use function. The accessibility in this application is based on the land use base of Statistics Netherlands from 2000 and the city map of Weert. METRONAMICA requires the data to be in shapefile format.

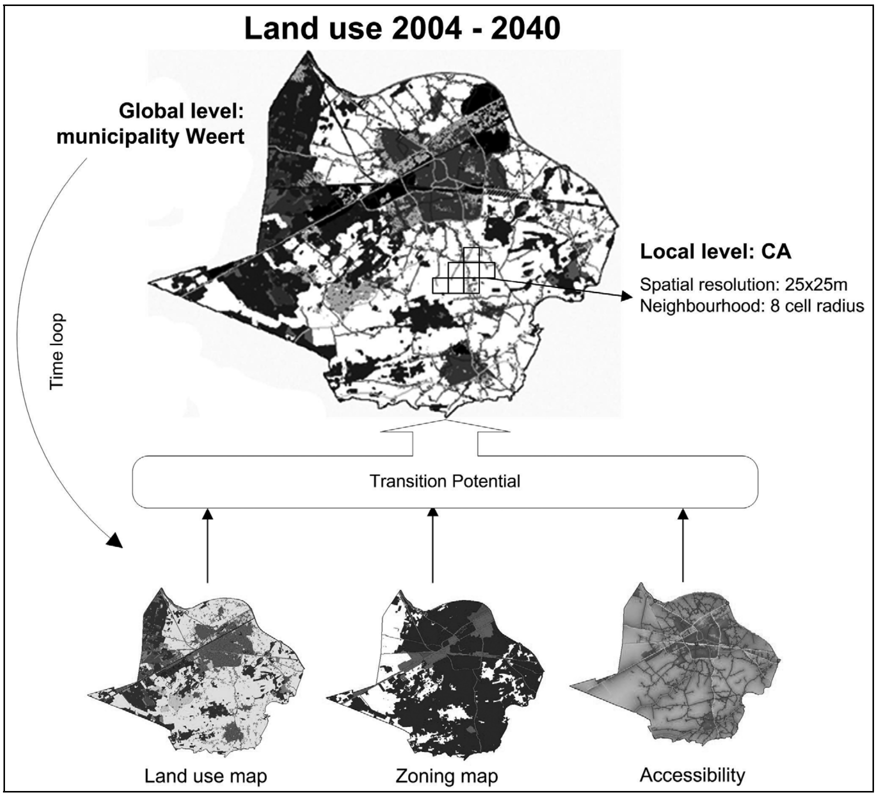

Fig. 1: Main input data and values

Development scenario

Before carrying out the modelling, a scenario was created considering future development for each land use function. Based on this scenario, for three variants the amount of cells per land use function was calculated until 2040 (see Tab. 1). Each variant is introduced via zoning maps: The "competition variant" allows growth from 2008 on only on the Kampershoek and after 2015 also within the entire municipality (except for protected areas). The "Moesdijk retail variant" does not allow any retail on the Kampershoek and the "Kampershoek retail variant" allows growth of retail only on the Moesdijk.

Model calibration

For calibration purposes, a time period of seven years (1997 until 2004) was taken into consideration. First, the macro model, which determines the demand for land use, had to be calibrated. It consists of a set of trend lines, representing demand of space over time. For each land use *function*, two cell values must be entered. Vacant land uses have no demand and are left out. Land use features have no transition potential and do not change during the simulation. They are left out either. The fist value equals the occurring cells per land use function in the land use map from the begin year. The last value depends on the estimated future development. It is possible to enter as many intermediate steps as needed. The simulation is forced to match the inserted cell numbers, implementing these constraints into the cellular automaton. For this application values where entered as shown in Table 1.

For each land use *function* a set of neighbourhood rules had to be calibrated, implemented by means of linear splines. Each spline determines the degree to which a land use *function* is attracted to or repelled by other land use functions, vacant states or features. The strength of the attraction and repulsion is defined by a function of distance for every land use. It means that each cell within the neighbourhood is weighted differently depending on its state and distance from the reference cell. If the attractiveness is high, the function will occupy a certain cell. If the attractiveness low, the function will look for more attractive cells to occupy. The weight may be positive, representing an attractive effect, or negative if two states are incompatible. The function includes distance and accounts for the effect that frequently a cells' effect is stronger the closer it is (WHITE & ENGELEN 1997, 239).

For each land use *function*, also the factor of accessibility to links and nodes had to be calibrated. Accessibility is subdivided into relative importance and distance decay. Relative importance ranks all existing transportation features on a scale of 0 = unimportant to 1 = important. The factor of distance decay determines how fast the importance lessens. A highway exit attracts people living in the distance. Its importance of 1 is divided into half after 100 cells. Municipal roads in contrast lose their importance sooner. The distance decay can also be negative, assuming that people do not want to live close by a noisy road.

Model validation

Validation is the process of measuring the model's prediction with independent data. For this application no additional validation data was available and a "goodness-of-fit calibration" had to be carried out. On the cellular level the '*goodness of fit*' was applied by calculating the *Kappa Index* with the Map Comparison Kit (MCK) (HAGEN-ZANKER et al. 2006). Kappa however, confounds similarity in quantity with similarity of location. Hence, two additional types of similarity were calculated: location (*Kloc*) and quantity (*Khisto*). *Location* in this sense depends to the spatial distribution of the different categories on the map. *Quantity* depends on the total number of cells taken in by each category found in the legend (the histogram) (HAGEN-ZANKER et al. 2006). As a rule is: *KHisto*KLoc* = *Kappa*. When having calculated the *Kappa*, the challenge remains in interpreting the obtained values. For instance a *Kappa* value of 0.81 might be found, but the question remains what that value signifies. As a solution to this problem, an additional map was created with the Random Constraint Match tool (RCM) available in the MCK. This tool finds locations of change randomly and evolves towards a 'speckled' map of small clusters (HAGEN-ZANKER & LAJOIE 2008). It creates a new map by minimally adjusting the original map from 1997, giving it the same frequency distribution of the categories as occurring in the map from 2004. The modified cells of the 2004 map are selected randomly. First decreasing land use is identified, then removed and randomly filled with increasing land use. The RCM map is compared to the real known land-use map from 2004. If the *Kappa* "RCM map – land use map 2004" is lower than the *Kappa* "simulated map 2004 – land use map 2004", the calibration is successfully. It shows the model performs well on a cellular level.

On the global level (the entire modelled area) polygons were measured with the help of Zipf's law. It assumes that the frequency of values (urban cell clusters of a certain size) is logarithmic proportional to their rank (number of cells belonging to the cluster). Zipf's law is true for northern European landscapes: few large clusters can be found (larger cities), some medium sized, but most clusters occurring are small (towns). For this application, the simulation was run from the land use map 1997 a total of 50 years into the future, resulting into a simulation map for the year 2047. After 50 years it becomes possible to evaluate if the transition rules are set in such way that the simulation captures urban dynamics.

Table 1: Number of cells and hectare (ha) per land use function modelled

Land use functions	2004		2015		2030		2040	
	No. cells	ha	No. cells	ha	No. cells	ha	No. cells	ha
Grass in build up	9460	591	8496	531	8816	551	8816	551
Sparse nat. Veg.	4207	263	4208	263	4320	270	4320	270
Agriculture	85059	5317	82992	5187	82512	5157	82192	5137
Forest	30872	1930	30880	1930	31840	1990	32480	2030
Urban	15433	964	16784	1049	15488	968	14960	935
Peri-urban	6411	401	6456	403,5	6512	407	6544	409
Industrial	4758	297	6384	399	6624	414	6784	424
Retail	145	9	192	12	240	15	288	18

4 Results

Calibration and validation

First the *Kappa* was calculated for the land use map 2004 and compared to the random constrained match map (RCM). The obtained value was 0.909. In a second step, the land use map 2004 was compared to the simulated map 2004. The transition rules for the simulation were changed and adapted, until the *Kappa* "land use map-simulated map" was higher than the one compared to the RCM map. Finally a *Kappa* of 0.915 was achieved.

Considering Zipf's law, two graphs were created (see Fig. 2). The graphs show the distribution of urban clusters in 2004 and 2047. The results show that a distribution equally to the usual Zipf's law distribution was not achieved. There are quite a lot small one-cell clusters and a few unique large clusters occurring. Especially between cell sizes of 100 and 10,000 clusters are occurring only once. When overlaying the trend lines from 2004 and

2047, the line for 2047 is slightly lower and bent into horizontal direction. In theory, it should capture the trend of growing cities. People abandon small towns and move to the urban fringe. But when looking at the data labels, in 2047 a total of 849 single cells occur, whereas in 2004 only 236 single cells occur. So actually an increase of small clusters takes place. But also medium-large clusters increase in the simulation for 2047. Compared to 2004 are here much more clusters to be found between sizes of 10 and 100 cells.

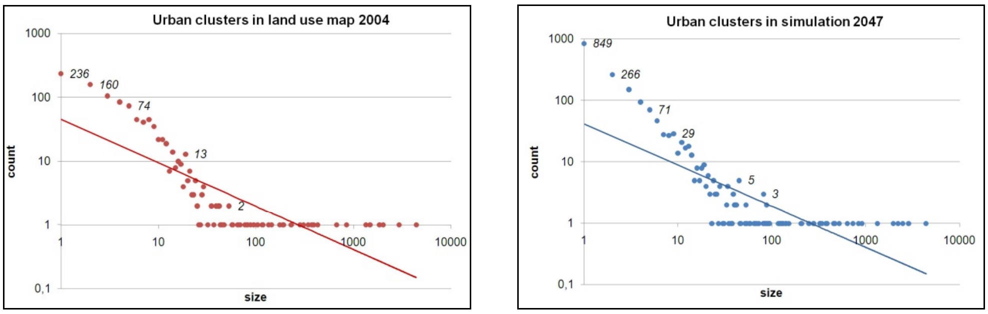

Fig. 2: Dispersal of urban clusters in 2004 and simulation 2047 (cluster size (amount of cells) plotted against count (number of clusters) on a logarithmic scale)

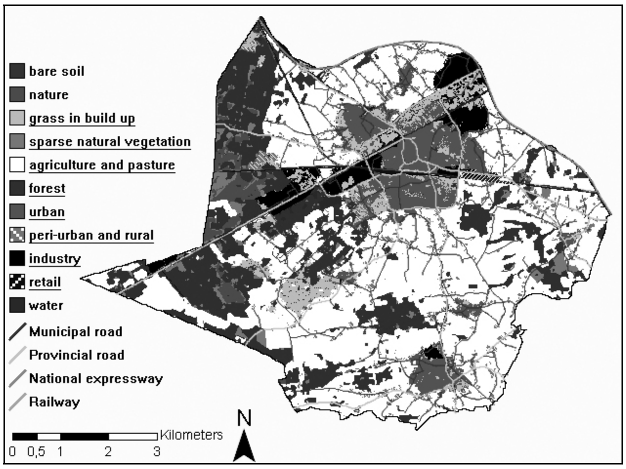

Fig. 3: Simulated map 2040, low grow scenario, competition variant with "N280 changed"

Simulation

Generally, not many significant changes take place. Main differences are occurring in industrial growth and urban shrinkage. Urban shrinkage is replaced mainly by the land use category grass in build up and new industrial areas replace agricultural cells. New developing cells of the land use classes nature and forest emerge along already existing natural and forested areas. The higher the growth in urban land use, the less cells are relocated. When comparing differences between the scenarios, industrial growth takes place first at the Kampershoek area, later also on agricultural land south of the railroad. But industrial cells emerge here only when the Kampershoek is completely filled by industrial land use. Retail has no negative influence on urban land use. If the N280 is not relocated, urban remains north of the Moesdijk area. Instead, shrinkage takes place within the city centre of Weert. The two scenario variants “Moesdijk” and “Kampershoek” were implemented via zoning maps in METRONAMICA. As retail is not allowed anymore on the Moesdijk area, it moves to the north of the Kampershoek and grows in a blobby cluster. The then available space on the Moesdijk area is however not taken over by industrial land use. It seems that the Moesdijk has only little attraction for industry. Instead, it emerges in the north of the city Weert, close to the highway. Figure 3 exemplary depicts the simulated map 2040 with the low grow scenario in the competition variant.

5 Conclusion and Outlook

Input data and variables: For a local application of METRONAMICA, results show that the input data has to be much more detailed. Using such data (for example digital topographic datasets in the scale 1:10.000), it would be possible to model more specific the land use functions. In order to set efficient transition rules, the urban area should be divided into sub-categories such as low-density building, high-density building, wholesale etc. Also regarding infrastructure for a local application, much more minor streets should be included. With the accessibility map applied, the amount of streets available was not sufficient. Besides improved input data, also different allocation mechanisms could be tested. The one applied within this study sums up by equal share the neighbourhood effect, suitability, accessibility and zoning. It would be possible to emphasize on the accessibility for example by giving it a higher weight in the final allocation, e.g. calculating it times four. When doing so, roads for example could have a stronger impact.

Cell size: With a cell size of 25 m the model starts to represent single properties and decisions of individuals (owners). METRONAMICA is not designed for modelling such. It models generalised trends in group behaviour and the impact those trends have on land use. But using the finest resolution available is not always a wise decision and reiterates the importance of adapting the cell size to the objects composing the landscape (MÉNARD & MARCEAU 2005, 710). However, results obtained within this study showed, that the applied cell size reasonably represented the land use processes in Weert. A clear drawback were inaccurate datasets. Coarser resolution hampers suitable geographic representation of patterns playing a key role in planning at the local level, e.g. natural areas or settlements.

Calibration measures: The *Kappa* index resulted in helpful measurements, keeping in mind the general critique: Can a cell-by-cell comparison account for an entire area? The validation measurement Zipf’s law has earlier been applied to evaluate simulations with METRONAMICA. But Weert fulfils different requirements: the area is too small and not enough clusters are available. Also the data structure hinders: streets, railroad and water bodies divide the urban areas into chunks that are then regarded individually. To overcome this problem, different data should be applied or the available data changed. Besides, Zipf’s law should rather be applied on much larger areas (e.g. national scale). It can be concluded that at this moment no sufficient methodology is available to validate modelling results on a high resolution, local scale. The evaluation had to be based on expert judgement.

Can METRONAMICA provide accurate results and usable support on a local level with a high spatial resolution?

METRONAMICA provides reliable results, but problems exist on the local level regarding the CA. For Weert, an area in the Netherlands, spatial development is planned, and only few dynamics exist. Similar circumstances can be found in other European countries. But the results achieved can support further planning decisions: the Kampershoek seems to be a good position for further industrial growth, retail should be realized on the Moesdijk area and it is not advisable to relocate the N280. Considering further research, it should be investigated if a similar application in a developing country achieves better simulation results. Here, the datasets can be expected to be of low quality, but at the same time much more unplanned dynamics exist that the cellular automaton could capture and simulate.

A weakness of CA is the inability of cells to move within the modelling environment. This becomes visible when dealing with migrating households or relocating firms as played a crucial role in this application. It would be interesting to apply agent based models. They focus on human actions and explore interactions between agents and the environment. Similar to CA consider agent based models a neighbourhood, which must not be regularly distributed. Agents have the possibility to change state depending on their neighbourhood and can also migrate to other locations at any distance from their current position (BENENSON & TORRENS 2004). However, most agents based models focus on situations to explore interactions between agents and the environment, rather than simulating landscape change. It is difficult to link agent behaviour to actual land areas and represent spatial behaviour. A new approach could be the combination of CA and multiagent systems (ibid).

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