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GIS-based 3D Urban Modeling Framework Integrating Constraints and Benefits of Ecosystems for Participatory Optimization of Urban Green Space Patterns

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1 ABSTRACT

Rapid urbanization is changing our environment coming along with decreasing green spaces in the urban areas. As these green spaces can provide so called ecosystem services contributing to human well-being, such as enhancing the micro-climate, noise reduction or provisioning of cultural values and space for recreation, the citizens' quality of life is affected by this development. However, urban development is the product of the interaction of multiple stakeholders and their awareness of these ecosystem services is low. Thus, tools are needed for better communication of how the provision of services is influenced by changes of the urban pattern applicable in stakeholder participation processes for urban development planning.

We present an urban modeling framework integrating parameters of ecosystem service provision in order to enable stakeholders to optimize the distribution and design of urban green spaces. The approach is developed and implemented for the case study of Altstetten, the most populated district of Zurich with about 28'000 inhabitants and an area of 742 ha. Two different modeling approaches are linked: 1) A Multi-Criteria Decision Analysis (MCDA) is carried out taking into account spatially explicit location conditions and spatial structures for an optimization of green space distribution at district level. 2) The resulting maps with land use information for each parcel are further processed in a rule-based 3D procedural urban model. This model is applying ecological rules of ecosystems' constraints and benefits for the distribution of green space elements on parcel scale. The resulting interactive procedural 3D visualization of possible urban green space patterns is a valuable basis for more informed decision-making in urban planning.

2 INTRODUCTION

The world is going through an intensive phase of urbanization. Today more than half of the world's population lives in urban areas (UN-Habitat 2008). On the one hand the concentrated population growth in urban areas permits to provide a wide range of infrastructure like effective public transport, public health, drinking water or waste disposal systems. On the other hand, the demands of different local actors compete with each other and cause an increasing pressure on the resource land in urban areas. However, interrelated with the increasing dimension of urban areas, the population and their need for resources like land or food and other services of the surrounding area grows (EEA 2006). Caused by this intense use, urban sprawl and thus the fragmentation of landscape and habitats increases while their quality decreases (Jaeger et al. 2010). However, urban green spaces are relevant object for both ecosystem networks and human well-being. Therefore they are essential for aspects of regional sustainability. Due to both further expansion and densification of urban areas green spaces tend to disappear and access to open and rural landscapes is vanishing (UN-Habitat 1996).

Thus, the aspired urban development combines the strategies of urban densification and the "green agenda" treating ecological and social aspects (UN-Habitat 2009, ARE 2011). One difficulty is the poor information transfer to the different stakeholders. 3D visualizations, which are easy to read even for laymen, can overcome communication difficulties (Hanzel 2007). Innovative procedural modeling approaches allow to easily produce large scale 3D city models based on design rules (Müller et al. 2006, Wissen Hayek et al. 2010). The CityEngine systems allows to produce such procedural 3D city models (www.procedural.com). In combination with an adequate indicator set, 3D landscape visualizations have shown to support stakeholders in the analysis of landscape changes (Wissen et al. 2008).

In this study an approach is presented, which integrates ecological and social aspects into urban modeling methods using multi criteria decision analysis and a procedural, shape grammar driven modeling approach.

We model urban behavior at district and at parcel scale to generate integrated and GIS-based 3D visualizations of possible urban scenarios.

3 RELEVANT ASPECTS FOR MODELING URBAN GREEN SPACES

Urban green spaces have a wide range of direct and indirect influences on human well-being, e.g. providing habitat to diverse species, supporting ecological processes, space for recreation or buffer area for storm water. The following chapters give a short overview of relevant aspects of urban green spaces.

3.1 Urban green spaces and human well-being

The perception of natural elements in our environment has a significant influence on physical activity, ability for restoration from stress and thus on our well-being, our performance and recreation (Tzoulas et al. 2007). The availability of refuge, nature and biodiversity correlates with the recreational potential of an environment (Grahn and Stigsdotter 2010). Therefore, urban landscape should be considered more intensely in urban planning (Jackson 2003).

The relationship of urban green space and human health was researched in several studies (Kaplan 2007, Grahn and Stigsdotter 2010, Pluhar et al. 2010). Plants, mainly trees, have a direct influence on our physical environment. They influence microclimate for instance by cooling (Robitu et al. 2006, Shashua-Bar et al. 2009), wind shielding and air filtering functions (Nowak et al. 2006, Jim and Chen 2008). Attractive outdoor environments give the opportunity to maintain social contacts, which in turn is important for health and play a central role in social integration and society's self definition (Maas et al. 2009, Seeland et al. 2009). With all these affects well designed urban green spaces enhancing the living space due to their services have as well a direct economic impact, namely they influence market prices of houses and land (e.g. Luttik 2000, Morancho 2003, Kong et al. 2007).

But wherever one can find positive effects, there are negative ones, too (TEEB 2010). There are basic disservices of ecosystems like pest damage caused by range weeds on farmland (Zhang et al. 2007), mice in kitchen (Marsh and Salmon 2010) or toxication by wild herbs, berries or mushrooms (Moro et al. 2009). Huge trees can prevent ventilation (Gromke and Ruck 2007) and many tree species and shrubs emit volatile organic compounds (VOCs), which react with NOx to produce ozone (Benjamin and Winer 1998, Owen et al. 2001). Benefit to one observer may be a handicap to another. For example, climate regulation in sense of cooling effect by shadowing may be a benefit because of energy economization in summer, while in winter times the effect is a disadvantage due to increasing energy consumption (Heisler 1986). Even the same yield like a medicinal plant may serve as medicine and provides a disservice as poison in the wrong dose (Moro et al. 2009).

Since particularly in urban areas predictable conflicts between people and nature should be avoided, potential disservices must be addressed for sustainably managing urban green (Savard et al. 2000, Lyytimäki and Sipilä 2009).

3.2 Ecosystem Services (ES) in urban areas

Ecosystems are a dynamic complex of life forms (plants, animals and microorganisms) and their nonliving environment interacting as a functional entity (MA 2003). These interactions are described as ecosystem processes and ecosystem functions, which offer a flow of vitally important services (e.g. food, water or energy) to facilitate human life. Ecosystem functions exist independent from humans whereas services are defined as the benefits people obtain from ecosystems and are thus dependent of human needs (MA 2003). Ecosystems require space and soil of adequate quality to ensure the ability to provide high quality ES (Brauman and Daily 2008).

This concept of ecosystem services has become a relevant approach to link ecosystems and human welfare (Fisher et al. 2009). The Millennium Ecosystem Assessment (MA 2003) proposes four categories of ES:

- Provisioning services such as food, fresh water, fuel wood or genetic resources
- Regulating services such as climate regulation, disease regulation or pollination
- Cultural services such as recreation, esthetic, spiritual or intellectual inspiration
- Supporting services such as soil formation, nutrient cycling or primary production

In order to protect fragile ecosystems and avoid fatal land use conflicts (Vihervaara et al. 2010), decision-makers should consider ES (Fisher et al. 2009, TEEB 2010).

Outsourcing the production of diverse requested ES like food production or waste disposal out of cities to its hinterlands allows expanded urban areas. But there are ES, which have to be produced locally, like air filtration or noise reduction, esthetical or educational services (Bolund and Hunhammar 1999, Yli-Pelkonen and Niemelä 2005).

In summary, ecosystem or landscape functions can provide services as well as cause disservices (Lyytimäki and Sipilä 2009). The specific definition and range of this concept of services is still subject of ongoing discussions (Boyd and Banzhaf 2007, Brauman and Daily 2008, Fisher et al. 2009, de Groot et al. 2010). In particular one discussion focuses on the definition of services at landscape scale.

3.3 Ecosystem Services and landscapes

Landscapes spatially form the lived and experienced human environment. They enable both individuals and the society to fulfill physical and mental needs. As a resource they have diverse functions: They are living space for humans, animals and plants, provide area for recreation and identification and they are a spatial expression of the cultural heritage. Furthermore, they contribute to creation of economic value. Landscapes are dynamic interactive systems and developed based on the interrelationships of natural factors, such as stones, soil, water, air, light, fauna and flora, with human use and design (BAFU 2010:23).

At landscape scale the focus is on the aggregate of ecosystems and the built environment. Thus the concept of ES should be widened for landscape considerations. De Groot proposed the category “carrier functions” to accommodate built structures (de Groot 2006). He described and categorized the landscape functions (which provide services) in five classes:

- Regulation (e.g. air filtering, prevention of soil erosion)
- Habitat (refuge and reproduction)
- Production (e.g. food production, energy resources, fiber)
- Information (e.g. reflection, recreation)
- Carrier functions (e.g. habitation, mining or waste disposal) (Groot 2006).

3.4 Ecosystems under pressure

Even though a considerable part of the human population lives in cities, humans are still highly dependent on ES. Growing human population increase the demand for ES. Thus the significant degradation of ecosystems and their ability to provide ES of high quality poses a threat to human well-being (MA 2003).

The capability of ecosystems to provide ES is dependent on their structure and on their intactness. Hence pattern quality plays a major role in urban ES provision (Alberti and Marzluff 2004, Yapp et al. 2010). Thus, the management of urban green space to facilitate the provision of ES takes up a key role in urban planning (Young 2010).

3.5 Modeling urban Ecosystem Services

A model is a substitute for real systems (Ford 2009:3). They represent selective aspects of interest to enable targeted analyzes in order to learn something new about the represented systems (Ford 2009). Scientific models are a simplification of reality, testable, allow calculations, measurements and explanations and they are fictive (Franck 2002). The desire and thus the attempt to understand the relations between spatial patterns and their impacts on sociocultural and biophysical processes leads to complex combined human-nature models (Altwegg et al. 2011, Pickett et al. 2011).

For sustainable urban development and green space management participation is essential (UN-Habitat 2009). There is no universal solution for successful participation, but an effective communication is pre-condition. Further, modeling approaches are indispensable in order to assess and communicate consequences of policies and strategies. However, the highly complex models are hardly understandable and are mostly so called black boxes, which generate accurate but hardly comprehensible scenarios. Therefore, in communication processes, where transparency and traceability are important characteristics to avoid misunderstandings, the simplicity and transparency of the models is one important requirement to develop comprehensible and valuable scenarios of landscape development supporting participatory elaboration of strategies.

3D landscape visualizations combined with relevant indicators have shown to be comprehensive communication tools both for experts and laymen (Grêt-Regamey et al. 2008, Wissen et al. 2008). However, visualizing urban areas applying conventional 3D visualization methods, placing 3D objects at the geographically correct position, results in highly time consuming tasks due to the high amount of individual objects. In contrast, innovative software programs, in which design rules encoded to shape grammars are leading the simulation procedure, allow to easily produce multiple alternatives of urban pattern development (Müller et al. 2006, Halatsch et al. 2008). These procedural, shape grammar based modeling approaches offer powerful tools enabling quick, beneficial and competitive 3D visualizations of complex city models (Ulmer et al. 2007, Wissen Hayek et al. 2010b). Grammars have already been defined to shape the urban environment, yet the procedural modelling approach for sustainable urban development still lacks encoding and integration of the contribution of the natural environment to urban qualities (Wissen Hayek 2010a). Overall, there is a need for a new type of model, which (1) focuses on the domains of interdisciplinarity in order to allow a more holistic approach and (2) is suitable for collaborative urban development platforms (Wissen Hayek et al. 2010a, Todorov and Marinova 2011).

4 CASE STUDY AREA

The 3D urban model is developed for the case study area Limmattal (valley of the river Limmat), an agglomeration in the northwest of Zurich. Special focus will be laid on Altstetten, the most populated city district of Zurich. It comprises an area of about 7,5km^2 and a population of 29'740 (about 3'965 inhabitants/km^2) (Statistik Stadt Zürich 2010).

Altstetten is a typical Swiss suburb and has a representative character. It combines local recreation area, residential area and industry in tight space. Moreover, it plays an important role as transit area and gate to the Swiss Plateau (Mittelland), as arising living space for a heterogeneous population and, with its large population, as an important city district of Zurich. Thus, this focus area is ideal for analyzing different possible future situations and development strategies. Results will be transferable to other (inter-) national areas with similar characteristics.

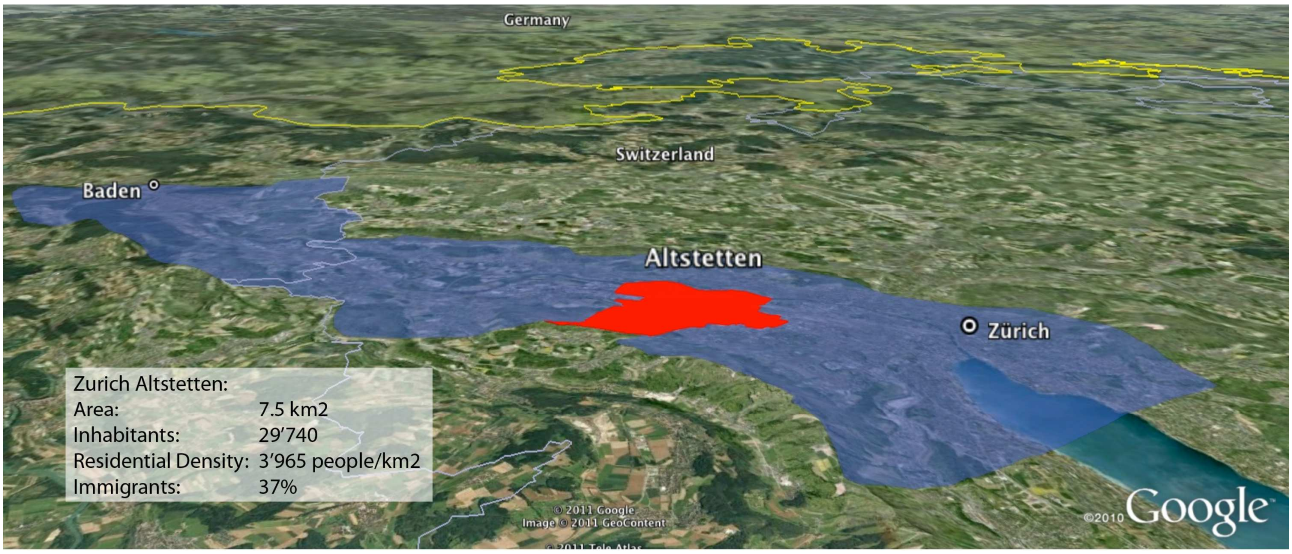

Fig. 1: Overview of the case study area Zurich Altstetten.

5 METHODS TO OPTIMIZE URBAN GREEN SPACE DISTRIBUTION

The complex problem of modeling urban patterns can be split in scale specific sub-problems to enhance comprehensibility. In this case study two approaches are combined (Fig. 2). First, in order to find an optimized urban green space distribution on district scale, a Multi Criteria Decision Analysis (MCDA, see for examples Malczewski 1999) is set up. The correlation of multiple parameters and conditions is used to calculate optimized new future urban pattern scenarios for the years 2030 and 2050. Output will be a land-use map with a resolution of 25 m^2.

Second, at parcel scale the distribution of landscape objects will be modeled. The required amount of green space elements like trees, shrubs, water ponds, or rocks is allocated depending on the parcel's function provided by the resulting GIS-maps of the MCDA. The spatial distribution of individual objects inside the urban green spaces is then modeled directly in a procedural 3D urban model based on rules according to green space types. Output is an interactive GIS-based 3D urban landscape model providing three-dimensional views of urban landscape patterns.

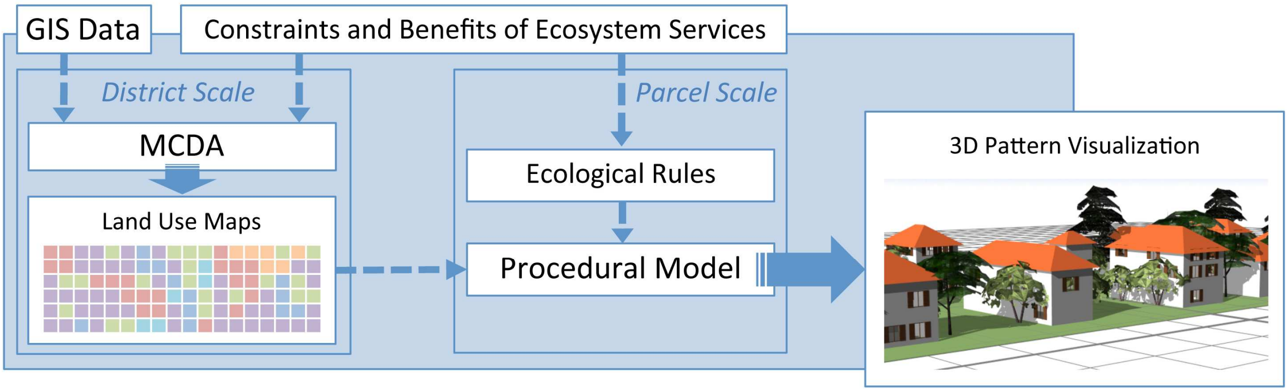

Fig. 2: Overview of the 3D urban pattern modeling workflow.

5.1 Multi criteria decision analysis

At district level there are diverse factors to be regarded, depending on the considered problem. The multi criteria decision analysis (MCDA) allows to combine these different factors and boundary conditions (Malczewski 1999).

The MCDA conjoins several objectives that are described by selected attributes. In case of ecological and social analysis of urban green spaces the availability of ecosystem services is taken as objective. The specific green space types are relevant attributes allowing for ES' provision. Thus, the goal is to optimize the distribution of the different green space types in order to maximize the availability of ES. Optimizing the distribution means optimizing land-use trade-offs. An initial evaluation and weighting of possible trade-offs is made by experts to generate an initial 3D visualization. This initial model serves as basis for problem analysis by stakeholders adjusting priorities and weights of the objectives. Thus, both environmental dilemmas like the potential disturbance of quality of ecosystem services or the occurrence of disservices (see section 3.1) and different stakeholder interests are addressed in this land use modeling process. The algorithm of *Linear Programming* allows calculating the spatial optimization of the land use. The stakeholder involvement is taking place at a later point, based on the modeling outputs of the initial expert evaluation.

Output of the MCDA is a map, describing the optimized land use structure (land use map). In order to model urban green space factors and quality requirements we focused on social and ecologically relevant objectives represented by the following exemplary selection of requested ecosystem services:

Ecosystem Service	Indicators	Relevant green space types
Food production	Net amount of agricultural production Diversity of agricultural usage	Agricultural land
Habitat	Amount of flagship species	Parks House gardens Civic greens Forests Abandoned land Ponds Fields Other urban green spaces
Social services	Comfortableness of the area Usability of the area Number of users	Parks House gardens Forest

Table 1: Selected ecosystem services, indicators and required green space elements used to model optimal urban green space distribution

5.2 GIS-based procedural modeling

GIS data is essential as a base for 3D landscape visualizations suitable for planning purposes. The procedural approach allows to combine GIS data with rules describing surface elements and structures.

Requested data sets for 3D visualizations are a digital elevation model (DEM) as a 3D surface, a land use map or an allotment plan with land use information to visualize landscape elements.

Parcels can get aligned to the DHM and linked with defined rules. Thus, implementing the rules on parcel lots results in reality based 3D visualizations of various levels of detail.

5.3 Integration of ecological knowledge into procedural urban modeling

For integrating ecological landscape aspects into urban models, ecological characteristics and relations have to be translated into discrete model parameters and functions (Wissen Hayek 2010b). For example the distribution of trees is an important parameter of landscape quality. Relative position is crucial to provide optimal shading in order to maximize the cooling effect in the summer (Raeissi and Taheri 1999). Other potentially relevant aspects of trees are size, age, species, water usage, pest resistance or shape (e.g. Kotzen et al. 2003, Gómez-Muñoz et al. 2010). The relevant aspects have to be selected depending on the local and case specific requirements.

The procedural, grammar based modeling approach allows to implement such parameters and relations as model-parameters and functions. 3D visualizations of the MCDA's resulting future urban patterns are generated in order to support participation processes. We apply a procedural approach, based on ecological and design rules using a computer language named CGA shape grammars. The latter are implemented in the CityEngine system (www.procedural.com). The system can quickly visualize urban environments of any size in a three-dimensional view, and thus supports evaluation of alternatives and iterative design workflows. Ecological aspects are encoded to rule sets structured in shape grammars producing patterns by sequentially applying rules on modeled land use patterns for spatial distribution of features. An implementation example of the distribution and height of trees on lawns is given in Table 2 and Table 3.

```
attr treedist = rand (6,10)                                # Distance between trees
attr grassheight = 0.1                                     # Height of grass
grasscolor = "#CCFF99"                                     # Color of soil
### - - - - - - - - - - - -   Species specific attributes   - - - - - - - - - - - - - - - - - - -  ###
treeX = "tree.obj"                                         # Import of the 3D tree object
treeX_height = rand(2,10)                                  # Height of the tree species X
treeX_width = rand(4,6)                                    # Crowd width of the tree species X
treeX_waterusage = 180                                     # Water usage of the tree species X
```

Table 2: Example of the defined *ecological attributes* in the grammar based model source code.

```
Lot     -->                                                # split east-west and plant trees along the houses
    split () { lawn | tree area | building | tree area | lawn}   # Create Lawn
Lawn  -->                                                  # Place trees with lawn in between
    extrude (grassheight), color(grasscolor)               # Insert 3D object on every 2nd place (50%)
TreeArea() -->                                             # Place trees in a specific distance to the house
    split (z) {~treedist:  Tree, Lawn}*                    # Define height
Tree -->                                                   # Report indicator water usage
    50%: i(treeX)
       t{(treeX_height/3),0,0}
       s(0, treeX _height,0)
    report("Water usage", treeX_water)
```

Table 3: Example of the defined *ecological relations* in the grammar based model source code.

Fig. 3: Example of a GIS-based 3D procedural urban modeling output applying rules given in Table 2 and 3.

6 RESULTS: APPLICATION EXAMPLE

We present an example of applying the procedural modeling approach on district level in our case study area Altstetten on the land use map. We demonstrate how urban green space distribution can be visualized in order to assist participation in urban planning processes.

In order to present the current state we used the land register as data basis. In the land register parcels are defined and limited by its land use. The shapes form both a gap and overlap free surface, which is essential for visualizations of high quality. In the first step rules to represent specific land use types like fields, house gardens, forests, water and sealed areas such as buildings, streets or railways were defined. In a second step, these rules were linked to the parcels through the attributes. Thus each parcel has a rule describing its structure. To create the urban 3D visualization the rules are executed on the parcels. In that way, the 3D urban patterns can get adapted to problem- or site-specific requirements by changing the specific rule. Thus, such visualizations can assist planning processes like participation workshops as impacts of discussed policy strategies can get analyzed by adapting the rule set in real time. Combined with adequate indicators complex analyses are possible based on the 3D model.

Fig. 4: GIS-based 3D urban model of the case study site Zurich Altstetten.

7 DISCUSSION AND CONCLUSION

We presented a GIS-based procedural modeling approach considering ecological aspects in order to support participation in urban planning processes. Main goal is to integrate cause-effect chains of ecosystem services in a qualified modeling process for stakeholder participation. Thus the modeling system has to remain at a comprehensible complexity level to allow stakeholders to understand the consequences of their decisions. The highly complex correlation of residents, traffic and real estate can be modeled by existing systems, e.g. UrbanSim. We expand these complex modeling approaches by ecological aspects and visual processing preparing a basis for stakeholder discussions in urban planning participation processes. The integration of GIS-data and ecological parameters in the procedural modeling approach allows to produce spatially adequate thematic 3D visualizations. These are suitable for modeling landscapes and analyzing both qualitative and quantitative landscape aspects.

A next step will be the modeling of optimal green space element distribution in urban green space types to visualize and analyze the existing green space potential in form of indicator values of the current possible provision of ES.

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