Integrated Multi-Criteria Modeling and 3D Visualization for Informed Trade-Off Decision Making on Urban Development Options

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Abstract. Cities all over the world are faced with growing population pressure and are challenged by decreasing environmental quality. Development strategies and planning processes often fail to involve local environment knowledge. We present an approach to integrate environmental aspects into a two-step urban modeling framework, generating 3D visualizations from GIS-based and procedural modeling. The dynamic nature of this approach provides considerable support for transdisciplinary communication processes in urban planning.

Keywords. Procedural modeling; generic urban pattern design; understanding ecosystem services; multi-criteria decision analysis (MCDA); GIS-based modeling.

INTRODUCTION
Growing urban areas and increasing populations in suburban zones confront urban planning with increasingly complex problems in securing an economic, ecologically and socially sustainable development (UN-Habitat 2009). At the same time green spaces are declining in the urban areas, which even increases the challenges. Large sealed areas for example induce urban heat island effects, higher air pollution or extreme wind regimes (Gälzer 2001). Shortage of green spaces leads to a wide range of further deficiencies, such as lack in recreational spaces and outdoor leisure activity opportunities (Whitford 2001). All these effects impact the residents’ well-being (MA 2005). The costs for resolving these impacts are not properly taken into account in urban planning, yet.

The concept of ecosystem services (ES) is very suitable to demonstrate these environmental costs and to make them negotiable. ES are “the benefits people obtain from ecosystems” (MA 2005), for example the ability of trees to regulate microclimate by evapotranspiration and shadowing, rain water infiltration of unsealed areas decreasing storm water peaks and supporting ground water renewal, habitat provision for diverse species, or provision of space for recreation in form of urban green spaces and parks. Even if provision of most urban ES generally decreases with increasing urban density, there is significant potential for optimizing the quality of ES provision in the urban area at any given density (Tratalos 2007).

In urban planning processes, the heterogeneous actor groups’ diverse demands and requirements are unequally taken into account (Buchecker et al. 2003). Today particularly political and economic demands rule these planning processes. However,
in consideration of continuously decreasing urban qualities, it is very urgent to account for the environmental aspects in order to secure livable cities. Neglecting these aspects can have impacts on the economic viability of settlement areas in the long term. For example, families with small children or old people require sufficient recreational areas in a walking distance from their home. If those recreational areas are not available, they might move to another place. This leads to a shift in household types living in an area and in extreme cases to segregation. Quarters with very low living quality, which cannot attract well-situated households, might face decreasing apartment prices.

Therefore, considering stakeholders’ knowledge and interests is essential to address their specific needs adequately and maintain or increase living quality on quarter level. In this way not only locally relevant factors for urban quality can be identified but also robust solutions can be developed that the participants accept and support. Thus participation processes are important for sustainable urban landscape development (Mabelis et al. 2009). In this context, the difficult and as yet poor transfer of ecological knowledge is problematic. Not only communication from science to stakeholders and from project leaders and stakeholders to the concerned public has to take place but also the local actor’s ecological knowledge has to be integrated into planning and scientific processes. The central challenge is the effective integration of the relationships between ecosystem changes and their services’ quality into communication and participation processes. GIS- and rule-based 3D visualizations offer high potential to enhance interdisciplinary communication.

RELATED WORK

In the last years different approaches have been presented to integrate the concept of ES into planning processes aiming at enhancing policies that prevent the disadvantages caused by loss of ecological quality (Salles 2011). For example, a study in the Swiss alpine region integrates the concept of ES and economic valuation methods in a GIS platform to compare the impact of different scenarios on the ES’ value in order to demonstrate consequences of different developments to a region (Grêt-Regamey 2008). A shortcoming of this approach is that only prepared scenarios can be compared. In order to cope with urban development that does not follow an all-dominant master plan, an interactive decision-support tool is required that interactively can combine hard factors, for example house prices, urban density or available green space per person, with soft factors such as recreational quality or scenic beauty. For a creative and iterative trade-off process of these factors, the tool should generate concrete images of possible urban development patterns and link these with further calculated indicators of their qualities. In this paper we present a concept for a modeling framework integrating criteria for ES’ provision into urban land use modeling and allowing stakeholders for weighting and trade-off decision-making based on generic 3D urban patterns and linked indicators.

METHODS

We suggest a two-step modeling framework, combining a GIS-based spatial land use modeling approach with integrated 3D modeling and detailed visual output of urban pattern design.

The GIS-based modeling allows the integration of quantitative indicators like green space supply rate. The visual modeling part allows the assessment of soft indicators, for example the attractiveness of developments in a district for different actor and stakeholder groups.

**Modeling environmental aspects in urban sites**

We introduce a new approach for linking land use modeling in ESRI’s ArcGIS with a procedural urban 3D modeling, implemented in ESRI’s CityEngine. While ArcGIS allows an exact and spatial explicit modeling of optimal land use distributions, the main
advantage of the procedural approach with CityEngine is the ability to efficiently generate 3D urban models of any size based on a set of rules and conditions (e.g. Ulmer et al., 2007; Wissen et al., 2010). The two approaches are linked by the GIS-output Shapefile (file format of ESRI's ArcGIS) used as basis input for the procedural model.

The exemplary implementation of the modeling concept presented in this paper demonstrates: (1) the generalization of ecological knowledge, (2) its integration into land use modeling incorporating different thematic maps, and (3) its integration into procedural modeling and 3D visualization with Computer Graphics Application (CGA) shape grammar rules (file format of ESRI's CityEngine), as well as (4) the mutual interaction between land use modeling and procedural visualization. The latter is illustrated with a set of indicators.

Linking procedural visualization and GIS-based multi-criteria decision analysis
An existing integrated ecological and design based 3D urban visualization approaches (Neuenschwander et al. 2011) is supplemented by a GIS-based land use modeling approach (Figure 1). To this end, an urban green space typology is implemented that combines design and ecological aspects in urban design rules for specific green space types such as semi-private gardens or public parks. These rules are encoded to CGA shape grammar rules. Further, land use data is linked with spatial parameters of ecosystem service's provision and used for the GIS-based land use modeling. Output of this land use modeling is an altered land use Shapefile in which each polygon (=parcel) is attributed an optimized land use. This output Shapefile is used to define in the procedural urban 3D visualization the spatial structure on the broad scale. Firing the procedural CGA rules with
design specifications on the land use data, the procedural machine generates a 3D visualization of the urban area. It then can be used as communication tool in public participation processes. The stakeholders’ definition of the urban pattern's quality is then iteratively used in the GIS-based modeling to generate a feedback model optimization process.

**Integrating generalized ecological knowledge into modeling and visualization taking into account different spatial scales**

The concept of ES allows identifying ecological processes and indicators relevant to the urban patterns' quality assessment from economic and social perspectives (de Groot, 2006; Grêt-Regamey et al., 2008). To apply the rules and specifications of ES's provision in modeling processes, this complex knowledge has to be generalized, categorized and relatively weighted to local relevance.

We chose the urban green spaces' habitat function as an exemplary ES in order to analyze local ecological quality. Quality specifications and needed landscape features of the habitats comprise, for example, vegetation, habitat size and structures connecting different habitat patches (Opdam et al., 2007). These specifications are derived from literature and used to define rules of adequate urban pattern design. However, the fulfillment of these ecological rules can conflict with the demand for settlement density. An increased urban density is, however, required to prevent urban sprawl and green areas, which are essential for ES provision, to be transformed in built-up areas.

Spatial features like the required distances or structures of green space types as well as the required settlement density are implemented in GIS-based modeling at municipality up to regional scale. The implementation in GIS allows mapping and analyzing complex spatial structures and linking the relevant data such as urban parcels for example with household characteristics or population density figures. It also allows for regional context analyses like the spatially explicit demand and supply of inhabitants with regard to recreational area.

The goal of our simulation is the maximization of potential ES provision and therefore the optimal distribution of the different land uses in the area. A thorough weighting of the different aspects and possible tradeoffs between ecological aspects and urban density allows for modeling optimized urban structures. A multi criteria decision analysis (MCDA) implemented in ArcGIS conjoins the different spatial conditions, aspects and trade-off specifications by combining different weighted condition-maps. It generates a spatially explicit land use map, presenting an optimized urban pattern distribution according to ecological and density rules (Malczewski 1999).

The distribution and concrete visualization of the structural features, design requirements and needed vegetation patches on local scale, that is the parcel level, is performed with the procedural visualization tool CityEngine. The optimized land use map is imported into the procedural model. It defines the spatial distribution of the green space type polygons. Applying the procedural rules with the local ecological requirements on the green space type polygons, 3D urban patterns are rendered. In combination with the implemented indicators, this visual output allows for an integrative assessment of the impact of alternative urban pattern designs on an urban landscape's quality.

**APPLICATION EXAMPLE**

Based on an application example, we demonstrate how existing GIS data can be linked to further ecological information and improved to a high-end 3D model, that benefits participative planning processes.

**Case study site**

The modeling framework is developed for the case study of Altstetten, a district of the city of Zurich, Switzerland. Altstetten links Zurich with the Limmattal, one of its suburban regions. Altstetten as a city district comprises an area of about 7.5 km2 with a population density of about 3’965 inhabitants/km2 (Statistik Stadt Zürich 2010). It combines local recre-
As the Limmat Valley region is currently in an intensive phase of urban development, the proper elaboration of an adequate development strategy is essential for future landscape structures. This makes this region interesting for modeling urban development and assessing policy strategies. Altstetten is the most densely populated part of the city and as well as of the region. Therefore it is qualified to illustrate specific urban difficulties as well as general problems in growing agglomeration sites.

** Applying ecosystem services in GIS-based modeling**

ES provision generally depends on multiple factors. For example, the function of urban green spaces as habitat for the species Water Frog (Pelophylax) depends on the available vegetation, microclimate, available water elements and last but not least on its connectivity with other habitats suitable for water frogs in order to provide an ecological network. Not all factors are of equal importance: the availability of water elements is crucial while others like specific vegetation elements are compensable. In order to model the requested ES potential, a weighted combination of the relevant factors is necessary. As application example we present the model for the potential provision of habitat for the water frog in Altstetten.

In a first step, we assessed the relevant factors and identified appropriate datasets. The second step simplifies the complex data information by creating classes of interests.

We demonstrate the modeling workflow with two example factors: the distance to water elements that is essential for water frog habitat (Figure 2a) and the land use types (Figure 2b) describing the current spatial landscape structure. The bigger the distance to water, the less an area is appropriate as water frog habitat. A buffer zone with adequate distances around the water elements models this behavior. As a second example factor, different land use types are of different attractiveness for water frogs. While settlement and flowing waters are unattractive, meadows and wetlands are suitable. We represent the suitability with cost factors as a supplementary attribute in the GIS data. To enhance the habitat model’s complex-

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**Figure 2**
Example of relevant factors for habitat potential of water frogs (Pelophylax).
The two images show two relevant factor examples in the case study area: the distances to water elements a) and the land use b). In both illustrations: the brighter the blue, the more attractive it is for water frogs. a) The nearer a water element, the more suitable is the area for water frogs’ habitat. In this illustration we chose buffer distances of 5m, 10m, 30m and 100m. b) Different land uses are of different attractiveness for water frogs.

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**Figure 3**
The integrated suitability of urban green space in Altstetten as habitat for water frogs. The habitat potential is calculated based on different relevant factors implementing MCDA methods.
ity, we amend several further factors like street network, buildings and green space types. The model is user-defined and extensible to address additional requirements.

To guarantee the compatibility of the different factor maps when merging, they are all transformed in raster data with similar extents. Some factors like the existence of standing water bodies is essential for the frog’s existence, while high quality in other factors can valorize the land use type. Even in industrial areas for example are water frog habitats of high quality possible if adequate green spaces exist in spite of high disturbances by industry. The different factors have to be weighted relative to each other to compute the habitat potential by merging the different maps. This multi criteria decision analysis (MCDA) is a suitable means for the calculation of the frog’s habitat potential in an urban area.

Applying ecosystem services and design specifications in procedural modeling

For the implementation of environmental needs we supplement the approaches of automated urban 3D modeling (e.g. Beirão et al., 2008; Halatsch et al., 2008; Wissen Hayek et al., 2011) with a systematic and locally relevant urban green space typology (Figure 4).

To take advantage of 3D models for planning processes, exact modeling of relevant local spatial structures is important, but to assess the potential ES provision it is essential to also consider required spatial structures, modes of management and modes of functioning of affected ecosystems. A locally relevant land use typology, categorizing land uses of certain homogeneity, enables linking the concept of ES to settlement structures. Regarding ES, we propose a local relevant urban green space typology that defines 14 general and 4 special land use types: semiprivate and private housing; play-
ing fields; cemetery and parks; public spaces; traffic green; copse and waterside; allotment gardens; fallows; forests; grassland and fields; industry; trade and as special types: market garden; farm; church and track area. The types are site specific and they suffice to picture the green spaces in the case study area of Altstetten.

For procedural modeling with CityEngine, the typology is implemented in rule files in a proprietary programming language, the CGA shape grammar (Figure 5). A rule file consists of two parts, analog to the typology structure. While the header defines all the model’s attributes, the main rule part describes the geometric pattern structure and spatial element distribution per parcel.

### Linking GIS-based and procedural modeling approaches
To unify the two modeling parts we linked the typology and the GIS model using the CityEngine Shapefile import function (Figure 6). The ground parceling and further information of complex GIS analysis is imported into the procedural model and is referenced as the basic structure. Thus every parcel is linked with information of its green space type and the rule file describes how to generate the 3D model of this specific green space type.

The habitat potential information is used to identify the relevant regions for maximal effectiveness and efficiency. In our example we define where to support ponds to enhance the water frog’s habitat connectivity.

### CONCLUSION AND FUTURE WORK
We provide a generic 3D urban modeling and visualization tool, allowing stakeholders in participative processes to iteratively analyze their different desires’ and decisions’ consequences on the urban patterns’ quality. Besides spatially explicit land use modeling, considering different regional and local land use conflicts, our framework enables the generation of detailed 3D visualizations based on different local aspects like design guidelines and ecological requirements. The impact of different policies...
and development strategies on landscape and ecological aspects can be modeled, illustrated and assessed in one workflow.

The generic approach based on a set of ecological and design rules allows for model adaption for any case study by rule adaption. The procedural model's power is its vagueness by modeling environmental potentials that facilitates scenario and policy assessment. This may support the elaboration of concepts for the development of municipalities or districts, e.g. by testing proposed designs in early stages. The interaction between the GIS-model and the procedural visualization tool is still realized by static Shapefiles. The taking over of CityEngine by ESRI promises the realization of closer connection of these complementary modeling concepts.

To reproduce the urban environment in an adequate manner, the considered criteria should cover at least the three fields of sustainability: economy, society and environment. A certain number of criteria are required for model’s representativeness while the applicability depends on manageable complexity. Thus the proper identification of significant criteria is crucial for model’s quality.

A learning process can be initiated by support of the GIS-based generic 3D urban model. Asking stakeholders to weight the different demands as input to the multi criteria decision analysis shows them the impacts of their specific demands on the fulfillment of all other demands. This guarantees local and topical relevance and increases the modeling results’ significance. Combining quantitative indicators and the intuitively readable visualizations provides a powerful tool to understand and assess the relationships between land use change and urban pattern quality. This tool has high potential to facilitate better communication between experts of different fields as well as laymen and thus enhance participation processes. This will be validated in future experiments and empirical research.
REFERENCES
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